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How do the changes in musculoskeletal properties and oestrogen levels during the adolescent growth spurt affect landing technique in girls?

Catherine Y. Wild
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**How do the changes in musculoskeletal properties and
oestrogen levels during the adolescent growth spurt affect
landing technique in girls?**

A thesis submitted in fulfilment of the
requirements for the award of the degree

Doctor of Philosophy

from

University of Wollongong

by

Catherine Y Wild

BSc (Hons)

School of Health Sciences

2012

Dedication

I would like to dedicate this thesis to my parents, Glenys and Kevin, for always encouraging and inspiring me to shoot for the stars. You always make me believe that anything is possible.

‘Think, Believe, Dream and Dare’

– Walt Disney, 1901-1966

Declaration

I, Catherine Yvette Wild, declare that this thesis ‘How do the changes in musculoskeletal properties and oestrogen levels during the adolescent growth spurt affect landing technique in girls?’ submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Health Sciences, University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged in this thesis. This thesis has not been submitted for a degree at any other university or institution.

Catherine Yvette Wild

1st August 2012

Publications

This thesis includes chapters that have been written as the following journal articles:

- Chapter 2:** Wild CY, Steele JR, Munro BJ. Why do girls sustain more anterior cruciate ligament injuries than boys? A review of the changes in oestrogen and musculoskeletal structure and function during puberty. *Sports Medicine*. In press, July 2012.
- Chapter 3:** Wild CY, Steele JR, Munro BJ. Musculoskeletal and oestrogen changes during the adolescent growth spurt in girls. *Medicine & Science in Sports & Exercise*. Accepted for publication, July 2012.
- Chapter 4:** Wild CY, Steele JR, Munro BJ. Insufficient hamstring strength compromises landing technique in adolescent girls. *Medicine & Science in Sports & Exercise*. In review, re-submitted for publication, July 2012.
- Chapter 5:** Wild CY, Steele JR, Munro BJ. Does higher anterior knee laxity influence landing biomechanics in pubescent girls? *American Journal of Sports Medicine*. To be submitted for publication, August 2012.
- Chapter 6:** Wild CY, Steele JR, Munro BJ. Development of landing biomechanics throughout the adolescent growth spurt in girls. *Medicine & Science in Sports & Exercise*. To be submitted for publication, August 2012.

As the primary supervisor, I, Dr Bridget Munro, declare that the greater part of the work in each manuscript listed above is attributable to the candidate, Catherine Yvette Wild. In each of the above manuscripts, Catherine was primarily responsible for study design and data interpretation, and solely responsible for data collection and data analysis. The initial draft of each manuscript was written by Catherine, who was then responsible for responding to the editorial suggestions of her co-authors. The co-authors assisted in study design, data interpretation and manuscript editing. Catherine has been primarily responsible for responding to reviewer's comments, with assistance from her co-authors.

Catherine Yvette Wild
Candidate
1st August 2012

Dr Bridget Munro
Primary Supervisor
1st August 2012

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‘You can design and create, and build the most wonderful place in the world. But it takes people to make the dream a reality’ – Walt Disney

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Abstract

BACKGROUND

In girls, puberty is accompanied by the adolescent growth spurt, a large influx of oestrogen, as well as an increased risk of sustaining a non-contact anterior cruciate ligament (ACL) rupture. The rapid growth and hormonal changes experienced by girls throughout puberty are thought to play a role in this increased injury risk, contributing to altered lower limb inertial properties, ultimately affecting lower limb flexibility and strength, with the potential to influence landing biomechanics. However, the longitudinal changes in musculoskeletal structure and function, as well as oestrogen levels, in addition to the longitudinal development of landing technique throughout the adolescent growth spurt in girls, remains unclear.

THESIS AIM

The primary purpose of this thesis was to investigate the longitudinal changes in musculoskeletal structure and function, as well as the oestrogen levels, during the adolescent growth spurt in girls and the influence of these changes on lower limb landing biomechanics.

METHODS

Forty-six healthy girls, aged 10-13 years, were recruited for this longitudinal study based on their pubertal development (Tanner Stage II-III) and their time from peak height velocity (maturity offset; -6 to -4 months or 0 months). Participants were tested up to four times during the 12 months of their adolescent growth spurt, according to their maturity offset (Test 1: maturity offset = -6 to -4 months, Test 2: maturity offset = 0 months, Test 3: maturity offset = +4 months, Test 4: maturity offset = +8 months). During the laboratory test sessions, each participant's anthropometric characteristics, oestrogen levels, anterior knee joint laxity, lower limb flexibility, isokinetic strength and landing biomechanics were collected and recorded. The landing task performed was a horizontal leap movement, during which ground reaction forces (1,000 Hz), lower limb electromyography (1,000 Hz) and kinematic data (100 Hz) were collected. Monthly tracking was also conducted, so as to estimate maturity offset using

anthropometric data, as well as to determine monthly fluctuations in lower limb flexibility and strength.

Results from this longitudinal study were analysed and presented in four chapters (Chapter 3-6), with each chapter systematically contributing to the overall thesis aim. The primary purpose of Chapter 3 was to determine the longitudinal changes in anthropometry, anterior knee joint laxity, lower limb flexibility and strength, as well as the oestrogen levels, in pubescent girls during their growth spurt. Based on the findings from Chapter 3, the effects of variations in hamstring muscle strength (Chapter 4) and anterior knee joint laxity (Chapter 5) on the lower limb landing biomechanics of these pubescent girls were investigated. Finally, based on the longitudinal musculoskeletal changes displayed by girls in Chapter 3, the final experimental chapter of this thesis investigated the longitudinal changes in lower limb landing technique displayed by pubescent girls through their adolescent growth spurt (Chapter 6).

MAJOR CONCLUSIONS

Based on the findings of this thesis it was concluded that during the adolescent growth spurt, pubescent girls display rapid growth of their lower limbs, an increase in anterior knee laxity, as well as a lag in the development of their hamstring muscle strength relative to their quadriceps muscle strength. The combination of these rapid and differential musculoskeletal structural and functional changes are thought to decrease knee joint stability during landing and are likely to contribute to the changes in landing technique that were evident during this time of rapid growth. The outcomes of this research provide a greater understanding of the lower limb musculoskeletal structural and functional changes throughout the adolescent growth spurt in girls, as well as the influence of these changes on landing technique in these pubescent girls.

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Chapter 1

The problem.

INTRODUCTION

Between the ages of 5-10 years boys and girls display a similar risk of sustaining a non-contact anterior cruciate ligament (ACL) injury, with these injuries accounting for less than 1% of all knee injuries incurred by pre-pubescent children.¹ From the onset of puberty, however, the ACL injury rate for boys and girls becomes disparate, with ACL injuries contributing to 4.8% and 11% of all sport-related injuries in pubescent boys and girls, respectively.¹ By adulthood, women are exposed to a 2-8 times greater risk of sustaining a non-contact ACL rupture compared to their male counterparts who participate in the same sport.^{1,2} As the differential ACL injury rate between males and females becomes evident at the onset of puberty, it raises the question as to what changes are occurring in girls during puberty that may increase their risk of sustaining this injury.

Defined as the transitional period from childhood to adulthood, puberty is accompanied by the appearance of secondary sex characteristics, which are in part, the external expression of hormonal changes occurring during this time.³ Unlike boys, from the onset of puberty girls experience a large influx of oestrogen, which continually rises throughout this period of development and into adulthood (see Chapter 2, Section 1). Although oestrogen receptors have been located on the fibroblasts of the human ACL,^{4,5} there is much controversy around the notion of whether oestrogen affects the material and mechanical properties of the ligament, particularly in pubescent girls (see Chapter 2, Section 2). Regardless of any influence of oestrogen on the ACL, increased anterior knee laxity has been shown to predict non-contact ACL injury risk.⁶ However,

only four studies were located⁷⁻¹⁰ that have investigated the changes in anterior knee laxity in girls throughout puberty, with mixed results being reported (see Chapter 2, Section 2.4). Furthermore, only two of these studies were longitudinal in design and participants were only tracked once a year over 3 years,^{9, 10} which may not be frequent enough to ascertain changes in anterior knee laxity throughout puberty (see Chapter 2, Section 2.4). Finally, there is currently no research that has longitudinally tracked the changes in anterior knee laxity, as well as oestrogen levels, from the onset of and throughout puberty in girls. Therefore, given the gender disparity in ACL injury rates from the onset of puberty and the association between anterior knee laxity, oestrogen levels and ACL injury, research in this area is warranted.

In addition to the hormonal changes occurring during puberty, girls also experience a rapid increase in height and mass, referred to as the adolescent growth spurt.³ From the onset to the cessation of the adolescent growth spurt, girls have been shown to grow approximately 25 cm, with a peak rate of growth in height (referred to as peak height velocity; PHV) of 8-10 cm/yr (see Chapter 2, Section 1). During this spurt, girls experience not only rapid growth, but also differential timing of growth, whereby the peak rate of lower limb growth occurs prior to PHV (4.25 cm/yr) and growth of the torso occurs after PHV (4-4.5 cm/yr; see Chapter 2, Section 1). Interestingly, within the lower limb itself, the peak growth velocity of the foot occurs prior to the peak growth velocity of the shank and the thigh (see Chapter 2, Section 1). This rapid and differential timing of lower limb growth inevitably affects the inertial properties of the lower limb,¹¹ which in turn, are reported to affect functional parameters such as lower limb flexibility and strength (see Chapter 2, Section 3). Although research has demonstrated that girls display a lag in the development of their lower limb muscle strength, particularly strength of the hamstring muscles (see Chapter 2, Section 3.2), as well as a

peak reduction in flexibility around the time of PHV (see Chapter 2, Section 3.1), there is a lack of evidence pertaining to the longitudinal changes in these musculoskeletal functional properties during puberty.^{9, 12-14} Furthermore, most studies that have investigated musculoskeletal changes during puberty have categorised participants based on chronological age^{7, 12, 13, 15-18} rather than pubertal stage.^{14, 19, 20} In fact, given the variability in biological development among individuals of similar chronological age, age is of limited use when assessing maturity (see Chapter 2, Section 1). Therefore, in order to gain a greater insight into changes in musculoskeletal functional properties during puberty, a comprehensive longitudinal study in which participants are categorised into groups based on pubertal development rather than chronological age is required.

The rapid growth changes experienced by girls throughout the adolescent growth spurt are also accompanied by changes in lower limb landing biomechanics (see Chapter 2, Section 4). Interestingly, ACL injuries frequently occur when individuals land from a jump, particularly during landing movements that incorporate predominantly horizontal momentum,²¹⁻²³ contributing to 12-20% of all non-contact ACL injuries.^{2, 23} Despite this fact, much of the research pertaining to landing biomechanics displayed by pubescent girls has utilised drop-jump landing manoeuvres as the experimental landing task,^{15, 19, 24-26} a movement not considered to be sport-specific (see Chapter 2, Section 4). Furthermore, of the limited research pertaining to landing biomechanics in pubescent girls, the primary research focus has been solely on the knee joint, particularly in the coronal plane (see Chapter 2, Section 4). Given that foot placement, as well as hip motion, have been shown to affect knee motion and ultimately ACL injury risk in adult females,^{21, 27-29} there is a need for further research to

investigate the landing biomechanics of the entire lower limb displayed by girls throughout puberty.

Overall, there is a lack of conclusive evidence detailing the longitudinal changes in the musculoskeletal structural and functional properties and oestrogen levels throughout the adolescent growth spurt in girls. Furthermore, there is limited research investigating the comprehensive changes in lower limb biomechanics and landing technique during this period of rapid growth, such that there is a substantial gap in the knowledge in this field.

STATEMENT OF THE PROBLEM

The primary purpose of this thesis was to investigate the longitudinal changes in musculoskeletal structure and function, as well as the oestrogen levels, during the adolescent growth spurt in girls and the influence of these changes on lower limb landing biomechanics. To achieve this overall thesis aim, anthropometric characteristics, oestrogen levels, anterior knee joint laxity, lower limb flexibility and strength, as well as the landing biomechanics displayed by pubescent girls, were assessed up to four times during the 12-month period of their adolescent growth spurt. Participants were also progressively tracked to determine the monthly changes in their height, mass and lower limb flexibility and strength during the year.

Before the research was undertaken, a comprehensive review of relevant literature was conducted to provide the rationale for this thesis (see Chapter 2). The longitudinal study was then completed, with the results presented in four chapters (see Chapters 3-6), with each chapter systematically contributing to the overall thesis aim. The primary purpose of the first experimental chapter was to determine the longitudinal changes in anthropometry, anterior knee joint laxity, lower limb flexibility and strength,

as well as oestrogen levels in pubescent girls during the adolescent growth spurt (see Chapter 3). The results of this chapter highlighted that the time at which peak lower limb growth and PHV occurred, were critical time points during the adolescent growth spurt at which significant changes in hamstring muscle strength and anterior knee laxity, respectively, were evident. Based on these findings, the effects of variations in hamstring strength at the time of peak lower limb growth (see Chapter 4) and the effects of variations in anterior knee joint laxity at the time of PHV (see Chapter 5) on the lower limb landing biomechanics displayed by these pubescent girls, were investigated.

The results of Chapter 3 also highlighted that there was a need to investigate whether the longitudinal musculoskeletal structural and functional changes that occurred during puberty affected the technique displayed by the girls when they performed a dynamic landing task. Therefore, based on the longitudinal musculoskeletal changes displayed by girls in Chapter 3, the final chapter of this thesis investigated the longitudinal changes in lower limb landing biomechanics displayed by pubescent girls during the adolescent growth spurt (see Chapter 6). A summary of the findings from this thesis, together with the thesis conclusions and future recommendations, are then presented in Chapter 7. A schematic representation of the thesis structure and how each chapter was designed to systematically address the overall thesis aim, are depicted in Figure 1.1.

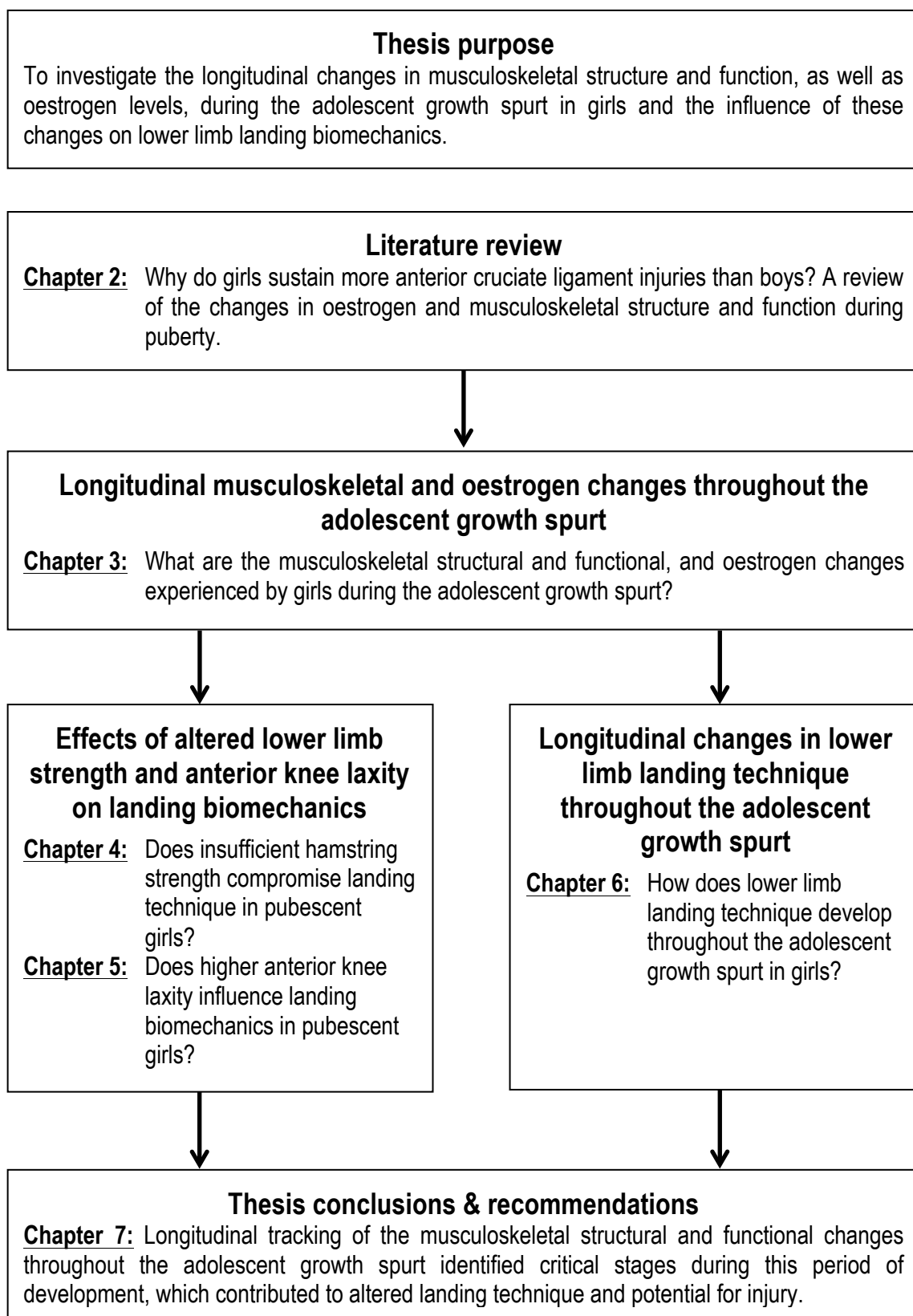


Figure 1.1: Schematic representation of the thesis structure, designed to systematically address the overall thesis aim.

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Chapter 2

Why do girls sustain more anterior cruciate ligament injuries than boys? A review of the changes in oestrogen and musculoskeletal structure and function during puberty

This chapter is an amended version of the manuscript: Wild CY, Steele JR, Munro BJ. Why do girls sustain more anterior cruciate ligament injuries than boys? A review of the changes in oestrogen and musculoskeletal structure and function during puberty. *Sports Medicine*. In press, July 2012.

ABSTRACT

Sport is the leading cause of injury among adolescents and girls incur more non-contact ACL ruptures than boys, with this gender-disparity in injury incidence apparent from the onset of puberty. Although the mechanisms for this gender-disparity in ACL injuries are relatively unknown, hormonal, anatomical and biomechanical factors have been implicated. Puberty is associated with rapid skeletal growth and hormonal influx, both of which are thought to contribute to alterations in ACL metabolic and mechanical properties, as well as changes in lower limb strength and flexibility, ultimately influencing landing technique. Therefore, the aim of this review is to explain (i) the effects of changes in oestrogen levels on the metabolic and mechanical properties of the ACL; (ii) changes in musculoskeletal structure and function that occur during puberty, including changes in knee laxity, and lower limb flexibility and strength; and (iii) how these hormonal and musculoskeletal changes impact upon the landing technique displayed by pubescent girls.

Despite evidence confirming oestrogen receptors on the ACL, there are still conflicting results as to how oestrogen affects the mechanical properties of the ACL,

particularly during puberty. However, during this time of rapid growth and hormonal influx, unlike their male counterparts, girls do not display an accelerated muscle strength spurt and the development of their hamstring muscle strength appears to lag behind that of their quadriceps. Throughout puberty, girls also display an increase in knee valgus when landing, which is not evident in boys. Therefore, it is plausible that this lack of a defined strength spurt, particularly of the hamstring muscles, combined with the hormonal effects of oestrogen in girls, may contribute to a more risky lower limb alignment during landing, in turn, contributing to a greater risk of ACL injury. There is, however, a paucity of longitudinal studies specifically examining the lower limb musculoskeletal structural and functional changes experienced by girls throughout puberty, as well as how these changes are related to oestrogen fluctuations characteristic of puberty, and their effects on landing biomechanics. Therefore, further research is recommended to provide greater insight as to why pubescent girls are at an increased risk of non-contact ACL injuries during sport compared with boys. Such information will allow the development of evidence-based training programs aimed at teaching girls to land more safely and with greater control of their lower limbs in an attempt to reduce the incidence of ACL ruptures during puberty.

INTRODUCTION

The highest prevalence of sports injuries in children and adolescents occurs at the onset of and during puberty, corresponding with the adolescent growth spurt.¹⁻³ When comparing the incidence of sport-related injuries during puberty, girls appear to be at a greater risk of incurring injuries such as non-contact ACL ruptures than their male counterparts,⁴ particularly in sports involving repetitive running, jumping and landing movements.⁵ In fact, females are greater than two-times more likely to rupture

their ACL compared with males,⁶ with ACL ruptures accounting for 37% and 23% of all knee injuries in females and males, respectively, from 11-18 years of age.⁴ This gender disparity in ACL injury incidence becomes evident from 11-12 years of age, coinciding with the onset of puberty.^{4, 6} However, no gender difference in ACL injury rate is apparent prior to the onset of puberty,⁷ contributing to only 0.2% of all knee injuries in girls and boys aged 5-10 years.^{4, 7}

Anterior cruciate ligament injury risk is multifactorial in nature with several potential risk factors having been identified and widely discussed in the literature.⁸⁻¹⁷ Some of these potential risk factors include hormonal (including the effects of oestrogen on the ACL), anatomical (including knee laxity, lower limb strength and anthropometric variables) and biomechanical factors (including the effects of altered landing biomechanics on the ACL).⁸⁻¹⁷ We postulate that differences in oestrogen levels between males and females, particularly from the onset of puberty, as well as the rapid changes in growth during puberty (including anthropometry, knee laxity, lower limb flexibility and strength), may play a role in the between-gender disparity in non-contact ACL injury incidence during dynamic landing movements.

This review aims to discuss published research that has investigated the hormonal, anatomical and biomechanical factors thought to predispose pubescent girls to a higher risk of non-contact ACL injuries. More specifically, this review will focus on: (i) the effects of changes in oestrogen levels on the metabolic and mechanical properties of the ACL; (ii) changes in musculoskeletal structure and function that occur during puberty, including changes in knee laxity, and lower limb flexibility and strength; and (iii) how these oestrogen and musculoskeletal changes impact upon the landing technique displayed by pubescent girls. The purpose of the review is to gain greater insight into factors that might contribute to the between-gender disparity in non-

contact ACL injuries from the onset of puberty, as well as to provide recommendations for future research in this important field of sports medicine.

An initial search in MEDLINE (1950+), CINAHL (1982-2011) and SPORTDiscusTM (1982-2011) in December 2011, limited to articles published in English, was conducted. Specific keywords were entered into the databases, including ‘anterior cruciate ligament’, which was combined (‘AND’) with the following keywords: ‘mechanical properties’, ‘metabolic properties’, ‘gender’. Other keywords included ‘puberty’ combined (‘AND’) with: ‘flexibility’, ‘knee’, ‘laxity’, ‘strength’, ‘landing’ and this yielded a total of 1,202 papers. These results were further limited by combining (‘AND’) with the specific keywords of ‘oestrogen’, ‘lower limb’, ‘girls’. Papers were only included in this review if they investigated the association between oestrogen and properties of the ACL, as well as if they investigated changes in lower limb flexibility or strength, knee laxity or landing technique in girls throughout puberty. Papers investigating upper limb flexibility or strength, for example, were therefore excluded from this review. Additional relevant papers were obtained from the reference lists of these primary sources (located in the databases), with unpublished studies excluded, leaving a total of 41 papers for review. Whilst only 41 papers were systematically reviewed, additional articles have been included to help explain and support information presented throughout the review.

1. Anthropometric and hormonal changes in girls during puberty

Puberty is the transitional period from childhood to adulthood, accompanied by the appearance of secondary sex characteristics, maturation of the reproductive system, and the adolescent growth spurt.¹⁸ Pubertal onset is often determined by measuring factors such as skeletal age,¹⁹⁻²¹ secondary sex characteristics,²¹⁻²³ time of menarche in

girls,^{18, 21, 22, 24} as well as PHV (peak growth in height during the adolescent growth spurt) and time from PHV (referred to as maturity offset).²⁵ As some children develop faster than others, chronological age is not a valid or reliable indication of maturation or the onset of puberty, particularly given that the growth spurt for boys lags 2 years behind that of girls.^{18, 21, 22, 26} In fact, due to the range of variability in anthropometric growth parameters and biological development (physiological growth) between individuals of the same chronological age during the growth spurt, chronological age has been suggested to be of limited use in assessing maturity.^{22, 24, 25, 27} Therefore, several methods have been developed to determine biological rather than chronological age. These methods, as well as the advantages and major limitations of each method, are outlined in Table 2.1.

During the adolescent growth spurt, from the onset to the cessation of growth, girls grow approximately 25 cm.²² The period of most rapid growth in height is referred to as PHV, and is reported to be approximately 8-10 cm/yr in girls.^{21, 22} This occurs around the ages of 11-12 years in girls,²⁵ corresponding with Tanner Stages II-III (see Figure 2.1).²⁸ The peak velocity for leg length growth during the growth spurt occurs before PHV, whereas peak velocity for sitting height growth occurs after PHV, corresponding with Tanner stages III-IV (see Figure 2.1).^{22, 25} Tanner et al.²² reported peak velocities of leg length and sitting height of 4.25 and 4-4.5 cm/yr, respectively, measured in 90 girls and boys throughout their adolescent growth spurt. In addition to increases in height and limb length during puberty, girls have been shown to display an increase in body mass of approximately 5.5 kg/yr from 8 to 18 years of age,²⁴ reflecting the growth in muscle mass and fatty tissue.²⁴ Furthermore, limb mass and, specifically, lower limb mass, increases by more than 3-fold in boys and girls from 6-14 years of age.²⁹

Table 2.1: A summary of methods used to indicate puberty in girls, as well as the advantages and major limitations of these methods.

Puberty indicator	Method	Advantages	Major limitations	Author/s
Chronological age	Age, determined from birth date	Quick, non-intrusive, non-invasive	Widely variable between individuals, poorly correlated with skeletal age	Faust, ²⁴ Hauspie et al., ²⁰ Iuliano-Burns et al., ²⁷ Tanner et al. ²²
Pubertal development (development of secondary sex characteristics)	Tanner Stages (I-V) determined through pictures and modified diagrams	Non-invasive, can be self-assessed	Intrusive and embarrassing (when examined by a clinician)	Tanner, ²¹ Tanner et al., ²² Taylor et al. ²³
Skeletal age (epiphyseal fusion of radius)	Hand and wrist radiographs and MRI	Most accurate and reliable indicator of pubertal/biological age	Expensive equipment required, exposure to radiation (radiographs)	Dvorak et al., ¹⁹ Hauspie et al., ²⁰ Tanner ²¹
Time from PHV (maturity offset)	Measured retrospectively from height measurements. Regression equation (using mass, standing and sitting height, age and gender)	Regression equation is quick, accurate and correlates highly with skeletal age	Time consuming if tracking longitudinally	Faust, ²⁴ Iuliano-Burns et al., ²⁷ Mirwald et al., ²⁵ Tanner, ²¹ Tanner et al. ²²
Menarche (time of first menstruation)	Time of menarche	Non-invasive, easily determined	Menarche is a late event during puberty, variable among individuals	Faust, ²⁴ Tanner, ²¹ Tanner et al. ²²

PHV = peak height velocity, MRI = magnetic resonance imaging.

Due to rapid growth of the long bones leading up to PHV, a rapid increase in both length and mass of the lower limbs occurs at this time, contributing to changes in the moment of inertia of the limbs.²⁹⁻³¹ This requires an increase in muscular torque to accelerate the limbs for a given movement, ultimately affecting muscle strength requirements during the performance of dynamic movement tasks, such as landing.^{30, 32} Jensen and Nassas²⁹ reported that lower limb moment of inertia relative to the transverse axis increases 10-fold from 6-14 years of age. Furthermore, differential timing of growth also exists within the limb segments whereby the more distal segments, such as the foot, experience their peak growth velocity before the more

proximal segments, such as the shank and thigh,²¹ again altering the inertial properties of the lower limbs.³⁰ Therefore, rapid changes in stature and limb dimensions throughout the adolescent growth spurt, particularly around the time of PHV, may affect functional parameters such as lower limb flexibility and strength, and ultimately performance during dynamic movements. Given that landing from a jump is a common non-contact ACL injury mechanism,³³ these rapid growth changes may possibly contribute to the greater number of ACL injuries sustained by females during this time.

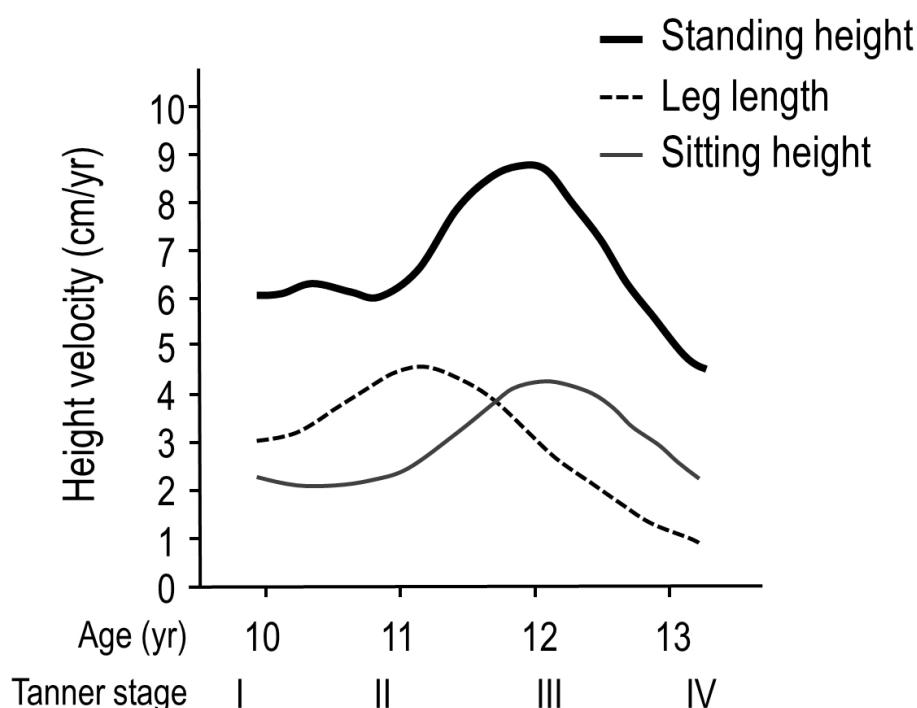


Figure 2.1: The timing of peak height velocity, according to chronological and pubertal stage, in relation to peak leg length and sitting height in girls (modified from Mirwald et al.²⁵ with permission, and Kanbur et al.²⁸). Peak leg length occurs prior to peak height velocity, at the age of 11.2 years, corresponding with Tanner Stage II. After peak height velocity is attained, at a mean age of 11.8 years in girls (Tanner Stage II-III), sitting height reaches a peak at a mean age of 12.2 years,²² which coincides with Tanner Stage III-IV.

Development of the external primary and secondary sex characteristics, such as breasts, genitals and pubic hair development, accompanies puberty, and are best determined using the Tanner stages of pubertal development.²¹ There are five Tanner stages whereby Stage I is representative of the pre-pubescent individual and Stage V

represents the adult or more mature individual.²¹ The development of secondary sex characteristics is, in part, the external expression of hormonal changes that occur during puberty.¹⁸ One of the major events occurring at the onset of puberty (Tanner Stage II) is the large influx of hormones, particularly the sex-steroid hormones such as oestrogen and testosterone.¹⁸ In girls there is a substantial influx of oestrogen at the onset of puberty. Oestrogen levels then continually rise throughout puberty, before reducing again during adulthood (see Figure 2.2).¹⁸ Similarly, boys experience a rapid increase in testosterone levels from the onset of puberty, an increase that is not apparent in girls (see Figure 2.2).¹⁸ Overall, it can be seen that the influx of oestrogen, as well as the vast differences in hormonal concentrations in girls and boys during puberty, may play a role in the high incidence of ACL injuries incurred by pubescent females.^{17, 34, 35}

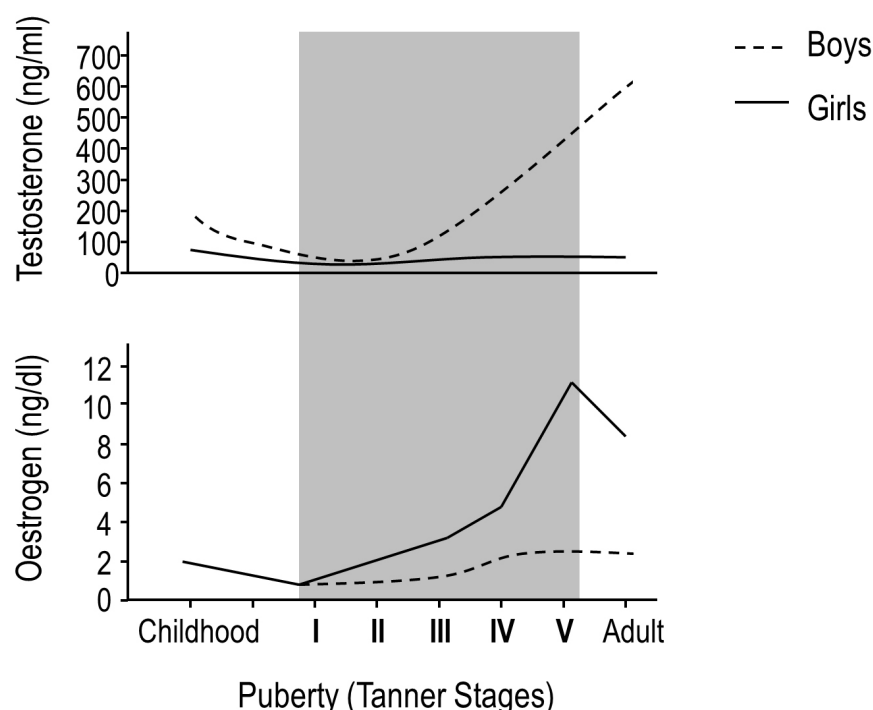


Figure 2.2: Levels of testosterone and oestrogen in boys and girls from childhood to adulthood. During puberty, boys experience a rapid influx in the levels of testosterone from Tanner Stage II, continually increasing throughout puberty into adulthood. Similarly, girls experience an increase in oestrogen levels from the onset of puberty (Tanner Stage II of pubertal development) to Tanner Stage III, a further increase from Tanner Stage III to IV and a final increase from Stage IV to V leading up to epiphyseal closure. Girls, however, do not experience the rapid testosterone influx that boys do, and boys do not experience the higher levels of oestrogen that girls do throughout puberty (adapted, with permission from Malina et al.¹⁸).

2. Effects of changes in oestrogen levels during puberty on anterior cruciate ligament injury risk

2.1 *Fibroblast proliferation and collagen synthesis*

Fibroblasts are crucial for maintaining the integrity of ligaments as they are responsible for preventing or repairing on-going microscopic damage to ligamentous tissues.³⁶ Collagen is produced by fibroblasts and forms the major load-bearing structure of the ACL.³⁷ The main types of collagen referred to in this review are Type I collagen, responsible for providing mechanical strength to connective tissues, and Type III collagen, responsible for tissue elasticity.³⁸

It has been proposed that the hormonal differences between males and females may be one factor to explain the greater number of ACL injuries displayed by females.^{35, 39} Reports have found both oestrogen and testosterone receptors on the fibroblasts of the human ACL^{35, 39} with no difference in the number of these receptors in young adult males and females (see Table 2.2).⁴⁰ Given the higher oestrogen concentration in females compared with males, sex hormones, particularly oestrogen, may have the potential to directly affect the structure, composition, and ultimately the mechanical integrity of the human ACL, contributing to the higher injury risk in females, particularly at the time of the pubertal oestrogen influx.

A study performed in the late 1990's exposed the ACL from a 32-year-old female to physiological and supra-physiological levels of exogenous oestrogen (0.0029-25 ng/mL) for 2 weeks.⁴¹ Results showed an initial up-regulation of fibroblasts in the first 3 days of oestrogen exposure.⁴¹ From day seven, however, a dose-dependent decrease in the proliferation of fibroblasts and rate of Type I pro-collagen synthesis was evident, with increasing levels of oestrogen.⁴¹ These results were confirmed by Yoshida et al.⁴² and Liu et al.³⁴ (see Table 2.2).

Table 2.2: A summary of the major findings and limitations of the literature investigating the effects of oestrogen on the anterior cruciate ligament.

Study	Animal vs human models	Major findings	Major limitations
Liu et al. ³⁵	Human model 13 females, 4 males	Oestrogen and progesterone receptors were located in the fibroblasts of human ACL	Large age range (18-78 years) for only 17 participants
Faryniarz et al. ⁴⁰	Human (cadaver) 8 females, 7 males	4-10% of ACL cells expressed oestrogen receptors No significant difference between males and females	All subjects were ACL injured patients
Yu et al. ⁴¹	Human (live, in-vitro) 1 female (32 year)	Day 1-3: decreased fibroblast and procollagen synthesis with increasing estradiol	Only 1 participant, limits the generalisability of results
Yoshida et al. ⁴²	Animal model (rats) 40 females	Decreased Type 1 collagen expression in rat ACL exposed to endogenous oestrogen vs ovariectomised rats	Animal model limits direct application of results to humans
Liu et al. ³⁴	Animal model (rabbits) 6 females	Decrease (40%) in fibroblast and collagen synthesis with increasing oestrogen (physiologic levels)	Small cohort size (n = 6) and no control group
Seneviratne et al. ⁴³	Animal model (ovine) 6 females	Oestrogen receptors located on ACL No change in fibroblast or collagen synthesis with increased oestrogen levels	Oestrogen exposure was short (only 4-6 days) Animal model limits direct application of results to humans
Toyoda et al. ⁴⁴	Animal model (rabbits) n = 18	20% increase in collagen synthesis when cyclic tensile load applied to ACL	Gender not specified Animal model limits direct application of results to humans
Lee et al. ⁴⁵	Animal model (porcine) n = not specified	Tensile load: increased mRNA expression of Type 1 collagen Oestrogen + tensile load: decreased mRNA expression of Type 1 & 3 collagen	Number and gender of subjects not specified Animal model limits direct application of results to humans
Lee et al. ⁴⁶	Animal model (porcine) n = not specified	Tensile load: increased mRNA expression of Type 1 & 3 collagen. Oestrogen + tensile load: decreased mRNA expression of Type 1 & 3 collagen	Number and gender of subjects not specified Animal model limits direct application of results to humans
Romani et al. ⁴⁷	Animal model 10 females, 9 males	Female vs. male ACL: greater stiffness (8.35 vs 4.23 N/mm-g) and failure loads (11.18 vs 5.67 N/g)	Animal model limits direct application of results to humans
Woodhouse et al. ⁴⁸	Animal model (rats) 40 females	High vs. low oestrogen: decreased deformation to failure (0.19 vs 0.79 mm) and increased energy prior to failure	Animal model limits direct application of results to humans
Slauterbeck et al. ¹⁷	Animal model (rabbits) 16 females	Decreased load at failure in ACL of oestrogen group (446 N) vs. control (non-oestrogen; 503 N)	Animal model limits direct application of results to humans

ACL = anterior cruciate ligament, **mRNA** = messenger ribonucleic acid.

Contrary to these results, Seneviratne et al.⁴³ exposed sheep ACL to oestrogen levels similar to previous studies^{34, 41} and found no change in fibroblast proliferation or collagen synthesis with increasing levels of oestrogen. These results imply that oestrogen does not have a negative effect on the metabolic properties of the ACL, such that there must be other underlying factors that predispose females to the greater number of ACL injuries compared with their male counterparts. It is important to note, however, that the ligament tissues in the Seneviratne et al.⁴³ study were only exposed to oestrogen for 4-6 days and so it is unknown whether the rates of collagen synthesis and fibroblast proliferation would have also decreased after six days, as they had in previous studies.^{34, 41, 42}

As the ACL tissue in the studies described above was harvested from different species (human, rabbit and sheep), between-study comparisons are difficult. However, there is more evidence suggesting that, regardless of the concentration, oestrogen may affect the metabolic properties and thus composition, of the ACL.^{34, 41} As these effects may reduce the ligament's ability to withstand load and increase the risk of injury, it is important to examine the effects of oestrogen and loading on the ACL.

2.2 *Effects of oestrogen and loading on the metabolic properties of the anterior cruciate ligament*

The ACL is continually subjected to tensile loads during walking, running and other activities of daily living and it is thought that this load is essential in maintaining integrity of the ACL fibres.⁴⁴ Toyoda et al.⁴⁴ exposed the ACL of rabbits to a cyclic tensile load of 80 mmHg vacuum force for 24 hours and found a 14% increase in Type I collagen fibres in the ACL that was subjected to loading, compared with the control (unloaded) ACL. This result was supported by Lee et al.^{45, 46} who reported an increase

in the messenger RNA (mRNA) expression of Type I collagen⁴⁵ and an increase in Type I and Type III collagen⁴⁶ when porcine ACL were subjected to a cyclic tensile load (see Table 2.2). It is postulated that an increase in the number of Type I collagen fibres in the ACL would provide greater strength to the ligament,³⁷ thus increasing the ability of the ACL to withstand high loads. As the ACL experiences tensile loads of up to 300 N during normal walking,⁴⁹ it can be assumed that the repeated application of this load, independent of oestrogen, may be beneficial to ACL health.

When the porcine ACL was subjected to cyclic tensile loads in an oestrogen environment (representative of the follicular, ovulatory and luteal phases of the female menstrual cycle), results showed, however, a down-regulation of the mRNA expression of Type I and Type III collagen.^{45, 46} Consequently, the presence of oestrogen may decrease the strength, and in turn the integrity, of the ACL. These results imply that the higher oestrogen levels in females negate the positive effects of everyday loading on the ACL, possibly placing females at an increased injury risk. This may be due to down-regulation of fibroblasts, which might result in reduced ligament strength.³⁷ However, it is important to determine whether these changes in the metabolic properties and fibre composition of the ACL affect the mechanical properties of the ligament, thereby making it more susceptible to rupture.

2.3 Mechanical properties of the anterior cruciate ligament in an oestrogen environment

Common sporting movements, such as jumping and landing, expose the lower limb, including the ACL, to forces up to 2-10 times body weight (BW).⁵⁰ In order to withstand these high loads generated during sport, the ACL must have adequate ultimate tensile strength and stiffness. As discussed in Section 2.2, although

controversial, there is support to show that oestrogen affects the metabolic properties of the ACL, irrespective of whether the ligament is loaded or unloaded.^{34, 41, 42, 45, 46} These changes in the collagen (Type I and III) content of the ligament will also affect the mechanical properties of the ACL, compromising factors such as ultimate tensile strength and stiffness, and its ability to withstand high loading.³⁸

Romani et al.⁴⁷ showed that female rats displayed significantly less Type III and substantially lower Type I mRNA collagen expression compared with male rats. Therefore, it was hypothesised that the female rats would display reduced stiffness and failure loads, as a result of reduced collagen synthesis, relative to their male counterparts. Interestingly, however, female rats displayed greater normalised ACL stiffness and failure loads compared with the male rats (see Table 2.2), indicating the female rats were better able to withstand load,⁴⁷ contradicting the results of previous studies on human ACL tissue.^{9, 51, 52}

In contrast, a recent study⁴⁸ examined the effects of high- and low-oestrogen environments, manipulated using the contraceptive pill, on mechanical properties of rat ACL. Higher oestrogen levels in the control group (no contraceptive pill; 46.7 pg/day/mL) resulted in the ACL displaying lower deformation to failure, as well as less energy absorbed prior to failure compared to ACL harvested from the experimental group, who had lower oestrogen levels of 32.9 pg/day/mL (contraceptive pill). Oestrogen levels were representative of those experienced during a normal human menstrual cycle,^{34, 41} as well as oestrogen levels of females using the contraceptive pill.⁴⁸ Slauterbeck et al.¹⁷ reported a decreased load to failure in the ACL of ovariectomised rabbits treated with an oestrogen supplement (serum oestrogen level 52 pg/mL) compared with ovariectomised rabbits not exposed to oestrogen (serum oestrogen level 15 pg/mL; see Table 2.2). The results of these studies^{17, 34, 41, 48} indicate

that the structural and mechanical integrity of the ACL is compromised in a higher-oestrogen environment (such as oestrogen levels similar to that experienced at the onset of puberty in girls), compared with a lower-oestrogen environment (oestrogen levels similar to males or pre-pubescent females). Therefore, changes in the mechanical properties of the ACL throughout puberty and how this affects joint laxity may provide further insight into the increased ACL injury risk characteristic in girls following the onset of puberty.

2.4 *Changes in knee joint laxity during puberty*

The ACL is one of the primary passive restraints responsible for stability of the knee joint.^{53, 54} It is thought that greater knee joint laxity may contribute to increased ACL injury risk due to an associated decrease in joint stability.¹⁴ For example, an increase in anterior tibial translation of one or more standard deviations above the mean has been found to significantly increase the risk of ACL injury in 1,198 male and female army cadets.⁵⁵ Given the association between oestrogen levels and mechanical properties of the ACL (see Section 2.3), the steep rise in oestrogen levels in girls during puberty (see Figure 2.2) may contribute to altered ligament properties and, in turn, knee joint laxity and ACL injury risk.

Whilst increased knee joint laxity is associated with greater ACL injury risk,⁵⁵ only five papers^{15, 56-59} reporting changes in joint laxity in girls throughout puberty were located (see Table 2.3). Quatman et al.¹⁵ reported that 28% of pubescent females displayed knee hyperextension, compared with only 10% of pubescent males. Girls also displayed greater generalised joint laxity, assessed using the Beighton and Horan Joint Mobility Index, throughout puberty compared to their male counterparts.¹⁵ Varying results, however, have been reported in other studies, whereby some have found an

increase in generalised knee joint laxity¹⁵ or anterior knee laxity⁵⁸ with increasing age or Tanner stage, whilst others have found a decrease in knee laxity with age or Tanner stage (see Table 2.3).^{56, 57}

Table 2.3: A summary of the literature highlighting changes in knee joint laxity in girls and boys throughout puberty.

Study	Study design	Participants	Age ^a	Test	Results
Quatman et al. ¹⁵	Cross-sectional (according to TS)	275 girls 143 boys	11-18 Pre-pubertal (TS I) Pubertal (TS II-III) Post-pubertal (TS IV-V)	Generalised joint laxity using the Beighton and Horan Joint Mobility Index	Girls: ↑ ($p = 0.042$) in generalised joint laxity with puberty Boys: no change ($p = 0.582$)
Baxter et al. ⁵⁶	Cross-sectional (according to age)	122 girls 110 boys	7-14	Ant/post, var/valg and int/ext rotation displacement using knee arthrometer	Progressive ↓ in knee laxity with age in boys and girls
Falciglia et al. ⁵⁷	Longitudinal (tracked annually for 3 years)	61 girls 62 boys	10.5-14.5 (TS I-IV)	Anterior tibial translation using KT2000 knee arthrometer at 134 N	Boys and girls: ↓ ($p = 0.03$) in laxity with TS Girls: ↑ in laxity (> 1 mm) from TS I-II
Costello et al. ⁵⁸	Longitudinal (tracked annually for 3 years)	22 girls	8-12 (pre-menarche)	Anterior tibial translation using KT1000 knee arthrometer at 133 N	↑ in knee laxity (> 2 mm; $p = 0.002$) with age
Ahmad et al. ⁵⁹	Cross-sectional (according to age and menarche status)	53 girls 70 boys	10-18 Pre-menarche girls (G1), post-menarche girls (G2), boys < 13 yr (B1), boys > 14 yr (B2)	Anterior tibial translation using KT1000 knee arthrometer at 20 and 30 lb (89 and 133 N)	G1, G2 and B1 displayed significantly greater knee laxity (1.5 mm greater; $p < 0.05$) than B2

a. Ages are presented in year ranges, mean or Tanner stages where stated.

TS = Tanner Stage; **ant/post** = anterior/posterior; **var/valg** = varus/valgus; **int/ext** = internal/external; **G1** = girls pre-menarche group; **G2** = girls post-menarche group; **B1** = boys < 13 years; **B2** = boys > 14 years.

It is important to note that of the five studies reporting changes in joint laxity in girls throughout puberty, only two grouped or tracked their participants according to pubertal development or Tanner stage,^{15, 57} whilst the remaining studies assessed their

participants purely based on chronological age.^{56, 58, 59} Whilst it is acknowledged that previous reports assessed girls according to menarche status,^{58, 59} this is a late event during puberty and does not reflect the differences in Tanner stage between individuals (see Section 1). Therefore, how the substantial influx in oestrogen in girls from the onset and throughout puberty affects knee laxity requires further investigation. Furthermore, given the rapid anthropometric changes during puberty (see Section 1), musculoskeletal structural and functional changes during puberty may provide further insight into the greater risk of ACL injuries in pubescent girls.

3. Musculoskeletal structural and functional changes in girls during puberty

3.1 Lower limb and trunk flexibility during puberty

Flexibility is defined as the extensibility of periarticular tissues to allow physiological motion of a joint or limb⁵³ and may be of fundamental importance during sport.⁶⁰ It is thought that there is an optimum range of joint flexibility that can prevent injury in the event that muscles or joints are overstretched during sport or activities.⁵³

During the adolescent growth spurt, around the time of PHV (11-12 years and Tanner Stages II-III in girls; see Figure 2.1), the skeleton grows at a faster rate than the supporting musculature. This growth differential between the skeleton and muscles is thought to lead to reduced flexibility or joint range of motion (ROM) of the lower limbs and trunk. Only four⁶⁰⁻⁶³ studies were located in the literature that assessed flexibility changes displayed by girls during puberty (see Table 2.4). Overall, these studies showed that girls displayed a decrease in flexibility just before or at the time of PHV,⁶⁰⁻⁶² indicating that the rapid growth at the time of PHV may be a contributing factor to reduced flexibility during puberty. One study,⁶³ however, indicated that the girls displayed an increase in flexibility throughout puberty. These between-study differences

in results may be due to discrepancies in the types of tests performed to quantify flexibility, as well as the joints examined. For example, two studies measured lower limb flexibility by asking the participants to try and touch their fingertips to the floor,^{62, 63} whereby the results may be confounded by tightness in the lower back rather than the lower limbs. Furthermore, only one of these studies was longitudinal in design. Given the lack of research in this field, further research is recommended to quantify changes to flexibility displayed by girls during puberty, using longitudinal study designs and valid and reliable flexibility assessment tests, to determine whether changes in flexibility during puberty play a role in the high incidence of non-contact ACL injuries in pubescent girls.

Table 2.4: A summary of the literature highlighting changes in lower limb and trunk flexibility in girls and boys throughout puberty.

Study	Study design	Participants	Age ^a	Test	Results
Loko et al. ⁶²	Cross-sectional (according to age)	902 girls	10-17	Lower limb flexibility (touching fingertips to floor)	↓ in flexibility just before PHV
Heras Yague et al. ⁶¹	Longitudinal (measured biannually for 3 years)	453 girls 509 boys	10-13 (measured according to height velocity)	Lower limb flexibility (touching fingertips to floor)	↓ in flexibility at PHV, with a peak ↑ in flexibility 8 months after PHV
Merni et al. ⁶⁰	Cross-sectional (according to age)	360 girls 460 boys	6-18	Standing hip extension (knee extended) and hip flexion ROM (knee flexed)	Peak ↓ in hip extension ROM at PHV; hip flexion ROM ↓ throughout puberty
Volver et al. ⁶³	Cross-sectional (according to TS)	77 girls	11-14 (TS I-V)	Trunk flexibility (distance of the fingertips past the toes)	↑ in flexibility from TS II-III, followed by a ↓ from TS III-IV

a. Ages are presented in year ranges, mean or Tanner stages where stated.

PHV = peak height velocity; ROM = range of motion; TS = Tanner Stage.

3.2 *Hamstring and quadriceps muscle strength during puberty*

As outlined in Section 1, puberty is accompanied by rapid growth, including a substantial increase in the moment of inertia of the limbs and, in turn, greater muscle strength required to control the limbs during dynamic movements.³⁰ Given that the ACL is commonly ruptured during abrupt landing tasks,^{6, 33} the role of muscles controlling the knee during landing, such as the hamstring and quadriceps muscles, and changes in the development of these muscles during puberty, are of vital importance. Furthermore, due to vast differences in circulating hormones in boys and girls during puberty (see Figure 2.2), it is postulated that between-gender differences in lower limb strength will also be evident during puberty.

The quadriceps muscles apply an extensor moment to the knee prior to landing in order to prevent the knee from collapse upon landing.⁶⁴ A total of eight papers investigating changes in quadriceps strength in girls throughout puberty were located (see Table 2.5). Every 4 months over 5 years Round et al.¹⁶ monitored changes in height, quadriceps strength and testosterone levels displayed by boys and girls, recruited from 8-12 years of age. Results of this study highlighted that boys and girls displayed similar increases in strength as they developed until 1 year prior to PHV. Clear gender differences in the rate of strength increases were then evident from 0-2 years after PHV, whereby boys demonstrated an accelerated strength development whereas girls did not, instead displaying a consistent pattern of strength gain (see Table 2.5).¹⁶ The authors concluded that the consistent increase in quadriceps strength in girls was proportional to the general increases in height and mass throughout the growth spurt. In contrast, the increased testosterone levels explained the greater increase in quadriceps strength displayed by the boys.

Table 2.5: A summary of the literature highlighting changes in hamstring and quadriceps muscle strength in girls and boys throughout puberty.

Study	Study design	Participants	Age ^a	Test	Results
Round et al. ¹⁶	Longitudinal (tracked every 4 months for 5 years)	50 girls 50 boys	8-12 (measurements were relative to PHV)	MVC of quadriceps, seated in 90° of knee flexion	Boys: 80-90 N/yr ↑ strength; girls: 20-30 N/yr ↑ strength 0-2 years after PHV
Parker et al. ⁶⁵	Cross-sectional (according to age)	284 girls 267 boys	5-17	MVC of quadriceps, seated in 90° of knee flexion	Boys: 55 N/yr ↑ strength; girls: 25 N/yr ↑ strength from 12 years
Segar and Thorsten sson. ⁶⁶	Longitudinal (tracked annually for 5 years)	7 girls 9 boys	11.5 Pre- vs post-puberty (according to TS)	Concentric and eccentric quadriceps strength at 45°, 90° and 180°/s	Boys: ↑ concentric (71-94%) and eccentric (87-100%); girls: ↑ concentric (53%) and eccentric (56%)
Ramos et al. ⁶⁷	Cross-sectional (according to age)	42 girls 45 boys	1. 11-12 (TS II-III) 2. 13-14 (TS IV) 3. 17-18 (TS V)	Concentric quadriceps strength at 60°/s using (Cybex 340)	↑ ($p < 0.001$) in quadriceps strength in boys (130 Nm) and girls (34 Nm) with age
Hewett et al. ¹²	Cross-sectional (according to TS)	100 girls 81 boys	11-18 Pre-pubertal (TS I) Pubertal (TS II-III) Post-pubertal (TS IV-V)	Concentric quadriceps and hamstring strength at 300°/s	Quadriceps and hamstrings: significant ↑ ($p < 0.05$) in males, not females across puberty
Costello et al. ⁵⁸	Longitudinal (tracked annually for 3 years)	22 girls	8-12 (pre-menarche)	MVC of quadriceps and hamstrings, seated in 20-30° of knee flexion	Quadriceps: ↑ 2 kg from 9.5-10.5 yr, ↓ 4 kg from 10.5-11.5 yr; hamstrings: no change with age
Ahmad et al. ⁵⁹	Cross-sectional (according to age and menarche status)	53 girls 70 boys	10-18 Pre-menarche (G1), post-menarche (G2), boys < 13 yr (B1), boys > 14 yr (B2)	MVC of quadriceps and hamstrings, seated in 45° and 90° of knee flexion	B2 vs B1: ↑ quadriceps (148%) and hamstring strength (179%); G2 vs G1: ↑ quadriceps (44%) and hamstring (27%) strength
Barber-Westin et al. ⁶⁸	Cross-sectional (according to age)	853 girls 177 boys	9-17	Concentric quadriceps and hamstring strength at 300°/s	Boys: ↑ quadriceps (40%) and hamstring strength (23%); girls: ↑ quadriceps (20%) but not hamstring strength (16%)

a. Ages are presented in year ranges, mean or Tanner stages where stated.

PHV = peak height velocity; **MVC** = maximal voluntary contraction; **TS** = Tanner Stage; **G1** = girls pre-menarche group; **G2** = girls post-menarche group; **B1** = boys < 13 years; **B2** = boys > 14 years.

These results have been confirmed by similar studies that have reported accelerations in the development of isokinetic (concentric and eccentric)^{66, 68} and isometric^{58, 59, 65} quadriceps strength after PHV and throughout puberty in boys, but not in girls (see Table 2.5). This highlights the androgenic role of testosterone in promoting increased muscle mass and strength.^{16, 18} Although oestrogen has some androgenic properties,¹⁸ it is not as potent as testosterone and, therefore, may explain why no accelerated development of muscular strength is evident in girls during puberty.^{16, 58, 65, 66}

In contrast to the studies described above, Ramos et al.⁶⁷ reported a significant increase in muscle strength with increasing age for both boys and girls, with no gender differences in strength (see Table 2.5). However, when normalised to body mass, boys showed an increase in strength of approximately 75 Nm/kg with age, whereas girls reported an increase of only 1-2 Nm/kg. Therefore, despite a lack of statistical difference between genders, a between-group difference of approximately 70-100 Nm of both absolute and relative torque could be considered clinically relevant. Also, the mean age of the boys and girls in Group One (11-12 years of age group; see Table 2.5) of this study were 11.8 and 11.9 years, respectively, with the boys in Tanner Stage II and the girls in Tanner Stage III. It is difficult therefore to make valid between-gender comparisons with respect to strength gains when the pubertal stages differed between the gender groups.

The hamstring muscles also play a vital role during landing movements by imparting a posterior drawer force to the tibia, thus acting as a synergist to the ACL.⁵⁴ Many studies reporting changes in lower limb strength in girls throughout puberty focus on development of quadriceps strength,^{16, 65-67} with only four papers located that

investigated changes in hamstring strength throughout puberty in girls^{12, 58, 59, 68} (see Table 2.5).

Similar to changes in quadriceps strength, a significant increase in peak concentric^{12, 68} and isometric⁵⁹ hamstring muscle torque is typically displayed by males throughout puberty, with no significant increases in torque displayed by females.⁵⁸ Furthermore, females display significantly weaker hamstring muscles relative to their quadriceps muscles with age when compared with their male counterparts.⁵⁹ In fact, Barber-Westin et al.⁶⁸ reported that females displayed a significant increase in quadriceps but not hamstring muscle strength with age. It is speculated that this decreased hamstring strength relative to quadriceps strength with age may result in less protection of the ACL during dynamic movements, potentially increasing the risk of ACL injury in females.^{59, 68}

Despite differences in study design and strength assessment methods used in the studies described above (see Table 2.5), there is general consensus that muscle strength is continuously developing in girls throughout puberty without an obvious growth spurt, and the rate of strength development is delayed behind the rate of skeletal growth, compared with boys.^{12, 16, 18, 58, 59, 65, 66, 68} The greater increase in quadriceps compared with hamstring muscle strength in girls during development creates a potential over reliance of the quadriceps and an under utilisation of the hamstrings,^{12, 59, 68} with possibly insufficient hamstring muscular torque being available to act as an agonist and aid the ACL during dynamic movements such as landing. Therefore, it is important to investigate whether these changes in lower limb strength alter the landing biomechanics of girls throughout puberty.

4. Lower limb landing biomechanics during puberty

Landing is a dynamic movement that requires a knee extensor moment to be applied to prevent the lower limb from collapsing while the body's downward velocity is reduced to zero.⁶⁴ Louw et al.⁶⁹ stated that landing from a jump was a complex activity, not often mastered by adolescents, as it requires adequate muscle strength and coordination, which is continuously developing and changing throughout puberty.¹⁸ In fact, poor landing technique, characterised by high ground reaction forces, increased knee joint valgus⁷⁰ and altered neuromuscular coordination,⁷¹ is a common cause of knee injury, particularly ACL injury, in pubescent girls.^{2, 33, 69} The ACL is also strained under knee abduction/valgus and rotational alignments that are commonly displayed by females during landing.^{12, 33, 72, 73}

Despite poor landing technique being a common cause of ACL injury, only seven studies were found that investigated the landing biomechanics displayed by girls during puberty or compared the landing technique of pubescent and pre/post-pubescent individuals (see Table 2.6).^{11, 12, 68, 74-77} Hewett et al.⁷⁵ reported no difference in the normalised peak vertical ground reaction forces generated by pubescent and post-pubescent boys and girls when the participants performed a box-drop landing manoeuvre. Similarly, Quatman et al.⁷⁶ reported females displayed no changes in the peak vertical ground reaction forces (normalised to BW) generated across puberty. Girls, however, displayed significantly greater loading rates during Tanner Stages II and III (45 BW/s) compared to during Stages IV and V (40 BW/s), highlighting the importance of neuromuscular activation patterns during this period of growth. Girls also displayed greater overall loading rates compared with the boys throughout puberty (40-45 BW/s and 30-35 BW/s), with this gender difference also evident among adult

males and females.^{70, 78} Although interesting results, these studies only investigated vertical ground reaction forces.^{75, 76}

Table 2.6: A summary of the literature highlighting changes in lower limb landing biomechanics in girls and boys throughout puberty.

Study	Study design	Participants	Age ^a	Test	Results
Hewett et al. ⁷⁵	Cross-sectional (according to TS)	87 girls 188 boys	TS II-V	GRF during box-drop landing	No significant changes in GRF over time or between-gender differences
Quatman et al. ⁷⁶	Longitudinal (measured annually for 2 years)	16 girls 18 boys	Yr 1: TS II-III Yr 2: TS IV-V	GRF during box-drop landing	↓ peak vertical GRF in post-pubescent vs pubescent males (0.2-0.4 BW); no change in girls
Ford et al. ⁷⁴	Longitudinal (measured annually for 2 years)	265 girls 50 boys	Yr 1: pre-pubertal Yr 2: post-pubertal (according to TS)	Ankle, knee and hip joint stiffness during box-drop landing	Males > stiffness vs females ($p = 0.001$), ↑ ankle ($p = 0.001$), knee ($p = 0.043$) and hip ($p < 0.001$) stiffness during pubertal growth vs females
Barber-Westin et al. ⁶⁸	Cross-sectional (according to age)	853 girls 177 boys	9-17	Ankle and knee separation distance (cm) during box-drop landing	No change ($p > 0.05$) in ankle or knee separation distance with age in males or females
Hewett et al. ¹²	Cross-sectional (according to TS)	100 girls 81 boys	11-18 Pre-pubertal (TS I) Pubertal (TS II-III) Post-pubertal (TS IV-V)	Knee valgus and medial knee motion during box-drop landing	Girls display ↑ ($p < 0.05$) in knee medial motion and valgus with age, but not boys
Ford et al. ¹¹	Longitudinal (measured annually for 2 years)	265 girls 50 boys	Yr 1: pre-pubertal Yr 2: post-pubertal (according to TS)	Knee frontal plane motion during box-drop landing	Girls ↑ peak knee abduction angle (1.6°) and moment (0.07 Nm.kg^{-1}) during pubertal growth, but not boys
Wild et al. ⁷⁷	Cross-sectional (according to age and time from PHV)	30 boys	Pre-pubertal (7-8 yr) Pubertal (13-14 yr) Post-pubertal (19-20 yr)	Muscle activation of quadriceps and hamstrings during landing	Pubescent males displayed altered neuromuscular activation vs. pre- and post-pubescent males

a. Ages are presented in year ranges, mean or Tanner stages where stated.

PHV = peak height velocity; TS = Tanner Stage; GRF = ground reaction forces; BW = body weight.

As the ACL is commonly ruptured during landings involving a horizontal approach,³³ horizontal ground reaction forces may be a more appropriate variable to investigate. Furthermore, neither study examined how these forces generated at landing were affected by changes in lower limb kinematics or neuromuscular activation patterns across puberty or whether these factors predisposed adolescent girls to a higher ACL injury risk relative to their male counterparts.

A decline in the ability to maintain lower limb, and particularly knee, alignment occurs in girls but not boys throughout puberty.^{12, 68} Hewett et al.¹² collected coronal plane knee kinematic data for girls and boys, matched for pubertal development, while the participants performed a box-drop landing manoeuvre. Girls in Tanner Stage IV and V exhibited greater peak knee valgus alignment compared with boys who were at the same Tanner stage of development (30° and 20° of peak knee valgus for females and males, respectively), whereas no gender differences in knee kinematics were evident prior to puberty. Ford et al.^{11, 72} also reported that pubescent females displayed greater total knee valgus motion compared with their male counterparts,⁷² as well as an increased peak knee abduction angle in girls, but not in boys during pubertal growth.¹¹ In contrast to these previous studies, Barber-Westin et al.⁶⁸ reported no change in knee valgus motion with age in females or males when the participants performed a box-drop landing (see Table 2.6). However, approximately 60% of all male and female participants in this study⁶⁸ landed with a valgus knee alignment, irrespective of age, a knee alignment that has been shown to be predictive of ACL injury risk.¹³ Ford et al.⁷⁴ reported that pubescent boys displayed significant increases throughout puberty in overall lower limb (ankle, knee and hip) stiffness during landing, whereas this increased stiffness was not displayed by females (see Table 2.6). It was suggested that decreased stiffness would be deleterious to landing, contributing to a decrease in joint stabilisation

and ultimately greater risk of non-contact ACL ruptures.⁷⁴ However, given the rapid changes in growth during puberty,^{21, 22, 25} the results of this study must be treated with caution as only two testing sessions, one year apart,^{11, 74, 76} may not be sufficient to ascertain the changes in lower limb landing biomechanics during puberty.

Although the studies described in this section suggest that during landing tasks, pubescent girls display an increase in valgus angle and medial knee motion combined with decreased lower limb stiffness compared with boys,^{11, 12, 74} these studies did not investigate the way the participants coordinated their lower limb muscles to align and stabilise the knee during landing. A recent study reported that pre-pubescent males tended to co-contract their quadriceps and hamstring muscles during a horizontal-leap landing movement,⁷⁷ a method though to stabilise the knee joint during landing⁷⁹ (see Table 2.6). However, post-pubescent males in the same study recruited their hamstring muscles before their quadriceps, most likely in an attempt to impart sufficient posterior tibial drawer to reduce the shear force imparted to the ACL by the subsequent quadriceps contraction.^{80, 81} Interestingly, the pubescent males co-contracted their lateral hamstrings and vastus medialis muscles followed by co-contraction of their medial hamstring and rectus femoris muscles. The authors concluded that in transition from childhood to adulthood, activation of the thigh muscles to stabilise the knee joint during landing appears uncoordinated, possibly contributing to the higher incidence of injuries displayed by this pubescent population.⁷⁷ However, this study was only cross-sectional in design and only included male and not female participants.

Overall, there is a paucity of research investigating changes in the landing biomechanics displayed by girls throughout puberty, particularly longitudinal studies. Interestingly, of the seven studies described in this section, only one examined a sport-specific landing movement,⁷⁷ whereas the other six studies examined a box-drop

landing manoeuvre.^{11, 12, 68, 74-76} Given that sport is the leading cause of injury in pubescent girls,^{82, 83} and the ACL is predominantly ruptured during movements involving horizontal momentum,³³ it seems that it would be more ecologically valid to examine the biomechanics of participants while they perform a sport-specific landing movement rather than a box-drop task. Research literature investigating entire lower limb biomechanics (ankle, knee and hip) during landing is also limited, with some studies focusing on only one joint (knee)^{11, 12} and predominantly in one plane of motion (coronal).^{11, 12, 68} Given that foot placement, as well as trunk and hip motion, affect motion at the knee,^{8, 84, 85} we recommend that future research should more comprehensively investigate the three-dimensional biomechanics of the landing technique used by girls performing a sport-specific task and how this changes throughout puberty.

5. Conclusions and directions for future research

Compared with boys, girls display a higher incidence of non-contact ACL injuries during sport, at the onset and during puberty. Although this between-gender difference in injury incidence is often attributed to the large oestrogen influx that girls experience during puberty, there are conflicting results as to how or whether oestrogen affects the metabolic and mechanical properties of the ACL, particularly in pubescent girls who have not yet begun menstruating. This is despite evidence confirming that oestrogen receptors are located on the ACL. Therefore, oestrogen still remains one factor in a multitude of other factors, which may play a role in the higher non-contact ACL injury incidence incurred by pubescent girls compared with boys.

There is a general consensus that unlike boys, girls do not display an accelerated increase in muscle strength during puberty and the development of their hamstring

muscle strength appears to lag behind that of their quadriceps strength. Despite controversy in the literature, there is evidence to suggest that girls display an increase in knee valgus alignment throughout puberty, with this knee posture having been associated with an increased risk of ACL injury. It is plausible that the lack of a substantial increase in strength in girls, particularly of the hamstring muscles, may impede their ability to stabilise their knee and protect the ACL during dynamic landing movements, contributing to a greater risk of ACL injuries. However, there is a paucity of longitudinal studies examining the lower limb musculoskeletal structural and functional changes (strength, flexibility and knee laxity) experienced by girls throughout puberty, as to how these changes are related to oestrogen fluctuations characteristic of puberty, or how these changes affect the way these girls land. Furthermore, to our knowledge, no research has investigated changes in the neuromuscular activation patterns or lower limb biomechanics displayed by pubescent girls while they are performing a sport-specific, horizontal landing movement. Therefore, further research is recommended to fill these gaps in our knowledge and to provide greater insight to explain why pubescent girls incur more non-contact ACL injuries during sport compared with boys. Such information will allow the development of evidence-based training programs aimed at teaching girls to land more safely and with greater control of their lower limbs in an attempt to reduce the incidence of lower limb injuries, particularly non-contact ACL ruptures, in pubescent girls.

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Chapter 3

What are the musculoskeletal structural and functional, and oestrogen changes experienced by girls during the adolescent growth spurt?

This chapter is an amended version of the manuscript: Wild CY, Steele JR, Munro BJ. Musculoskeletal and oestrogen changes during the adolescent growth spurt in girls. *Medicine & Science in Sports & Exercise*. Accepted for publication, July 2012.

ABSTRACT

The adolescent growth spurt is associated with rapid growth and hormonal changes, thought to contribute to the increased ACL injury risk in girls. However, relatively little is known about these musculoskeletal and oestrogen changes during the growth spurt in girls. **Purpose:** To investigate the longitudinal changes in oestrogen, as well as anterior knee laxity, and lower limb strength and flexibility throughout the adolescent growth spurt in girls. **Methods:** Thirty-three healthy girls, aged 10-13 years, in Tanner Stage II and 4-6 months from their PHV, were initially recruited. Participants were tested up to four times during the 12 months of their growth spurt, according to the timing of their maturity offset (Test 1: maturity offset = -6 to -4 months, Test 2: maturity offset = 0 months, Test 3: maturity offset = +4 months, Test 4: maturity offset = +8 months). During each testing session anterior knee laxity, lower limb flexibility and isokinetic muscle strength, as well as saliva measures of estradiol concentration were measured. **Results:** A significant ($p = 0.002$) effect of time on anterior knee laxity was found from the time of PHV, although no changes in estradiol concentration were displayed over time ($p = 0.811$). Participants displayed a significant increase ($p < 0.05$) in isokinetic quadriceps muscle strength over time, with no apparent increase in isokinetic hamstring muscle strength. **Conclusions:** We speculate that increased quadriceps strength,

combined with increased knee laxity and no accompanying hamstring strength development during the adolescent growth spurt in girls, might contribute to a decrease in their knee joint stability during landing tasks. These musculoskeletal changes could potentially increase ACL injury risk at the time of rapid height and lower limb growth.

INTRODUCTION

From the onset of puberty girls incur a high incidence of non-contact ACL ruptures, which contribute to 37% of all their recorded knee injuries.¹ This high ACL rupture rate in girls is not apparent prior to puberty,¹ whereby puberty is defined as the transitional period from childhood to adulthood, accompanied by the appearance of secondary sex characteristics and the adolescent growth spurt.^{2,3} It has been speculated that the rapid growth, as well as the musculoskeletal and hormonal changes, that occur during puberty may be factors contributing to this increased injury risk in girls.³

A major event marking pubertal onset in girls is the large influx of oestrogen.² Oestrogen has the potential to directly affect the structure and composition of the human ACL,⁴ inevitably affecting the mechanical properties of the ligament, including laxity.³ Cyclic fluctuations in oestrogen throughout the menstrual cycle have been shown to contribute to significant increases in anterior knee joint laxity from 0.7-1.5 mm in women.⁵ Due to the increasing influx of oestrogen in girls from the onset and throughout puberty,² it could be assumed that pubescent girls would also display an increase in knee laxity. However, when researchers have investigated changes in knee laxity throughout puberty, mixed results have been reported. For example, some researchers have demonstrated an increase in knee laxity (from 1-2 mm) throughout puberty in girls,^{6,7} whilst others have reported a decrease (approximately 2 mm) or no change in knee laxity throughout puberty.^{8,9} The lack of consistency, however, with

respect to the methods used to classify participant developmental stage, such as chronological age,^{6, 8} Tanner stage^{7, 9} or menarche status,^{6, 10} is a major limitation when trying to compare the results of these studies and highlights the need for further investigation in this field.

In addition to a large hormonal influx, puberty is also accompanied by the adolescent growth spurt.² During the adolescent growth spurt girls grow approximately 25 cm in height from the onset to the cessation of growth.¹¹ In fact, during the period of most rapid growth in height (PHV), girls have been shown to grow at a rate of approximately 8-10 cm/yr.¹¹ Interestingly, the peak velocity for lower limb growth in girls (4.3 cm/yr) occurs before the time of PHV, whereas the peak velocity for torso growth (4-4.5 cm/yr) occurs after the time of PHV. Furthermore, differential timing of growth exists within the lower limb itself, whereby the more distal segments such as the foot, experience their peak growth velocity before the more proximal segments such as the shank and thigh.¹² This differential timing of segment growth and consequent rapid changes in lower limb moment of inertia, is thought to contribute to altered lower limb flexibility and strength during the adolescent growth spurt, increasing the potential for lower limb injuries.^{3, 13}

The rapid increases in lower limb moment of inertia throughout puberty¹⁴ require greater strength for a given movement in order to accelerate and decelerate the lower limb segments during movements such as jumping and landing, in which ACL injuries commonly occur.^{13, 15} In particular, the quadriceps and hamstring muscles play a vital role in controlling the knee during landing.¹⁶ Research has shown that, from the time of PHV and throughout the growth spurt, males display a defined acceleration in the development of their quadriceps^{17, 18} and hamstring muscle strength,^{19, 20} which is not apparent in girls.¹⁷⁻²⁰ This lack of a muscle strength spurt, particularly of the

hamstring muscles,¹⁷⁻²⁰ could result in insufficient muscular torque being available to protect the ACL when girls perform dynamic movement tasks, potentially contributing to a greater injury risk. However, further research is required to provide greater insight into muscle strength development in girls during their growth spurt.

Due to the rapid increase in height and lower limb growth around the time of PHV, girls typically display a reduction in lower limb flexibility at this time,²¹⁻²⁴ potentially increasing the risk of lower limb injuries.²⁵ Whilst there is thought to be an optimum range of joint flexibility that may prevent injury in the event that muscles or joints are overstretched during an activity,²⁶ limited research pertaining to lower limb flexibility in adolescent girls exists. In fact, most researchers quantify lower limb flexibility during puberty by asking participants to touch their fingertips to the floor or past their toes.^{21, 22, 24} This measure of flexibility is likely to be confounded by the differential changes in lower limb and torso growth and, therefore, may not directly measure lower limb flexibility. Furthermore, most of these studies have been cross-sectional in design,^{22, 24} with only one being longitudinal,²¹ highlighting the need to longitudinally investigate joint specific ROM and flexibility of the lower limbs throughout the adolescent growth spurt in girls, particularly with respect to changes in height velocity.

There is a paucity of research pertaining to the lower limb musculoskeletal and oestrogen changes experienced by girls throughout the adolescent growth spurt. Within the limited published literature in this field, there is a lack of research examining changes longitudinally,^{6, 9, 18, 21} with most studies being cross-sectional in design.^{7, 8, 10, 17, 19, 20, 22-24} Furthermore, most studies investigating lower limb musculoskeletal changes during puberty have selected participants based purely on chronological age,^{8, 17, 20-23} which is not an accurate indicator of maturity in this

population.²⁷ Therefore, the purpose of this study was to investigate the longitudinal changes in oestrogen, as well as anterior knee laxity, and lower limb strength and flexibility throughout the adolescent growth spurt in girls. Based on the literature, it was hypothesised that girls would display a consistent increase in hamstring and quadriceps muscle strength without an apparent muscular strength ‘spurt’ and a decrease in lower limb flexibility around the time of PHV, as well as a rapid increase in oestrogen and anterior knee laxity throughout the growth spurt.

METHODS

Participants

Seventy-one healthy, female volunteers aged between 10-13 years were initially screened for their Tanner stage of pubertal development,¹² as well as their estimated time from PHV (maturity offset), to determine pubertal onset.² Due to ethical constraints and participant burden, each girl’s Tanner stage was self-assessed, with the assistance of a parent and/or guardian, using simplified Tanner stage line drawings of pubic hair development (see Appendix A); a valid and reliable measurement of pubertal development and sexual maturity (within 88% agreement).²⁸ Maturity offset was estimated using a sex-specific multiple regression equation based on each participant’s body mass, standing and sitting height, lower limb length and chronological age²⁷ (see Appendix B). This method can estimate maturity offset within ± 1 year 95% of the time.²⁷

Thirty-three girls satisfied the initial inclusion criteria for Test 1 (healthy female, aged 10-13 years, Tanner Stage II of pubic hair development, maturity offset = -6 to -4 months) and were recruited as participants. Girls were excluded if they did not satisfy the developmental inclusion criteria, had a lower limb injury that prevented them from

completing the experimental task, or had begun menstruating. The remaining 38 volunteers who did not satisfy the initial inclusion criteria for Test 1 were re-screened approximately 6 months later. Thirteen of these girls satisfied the inclusion criteria for Test 2 (Tanner Stage II-III and maturity offset = 0 months) and the remaining 25 girls were excluded from the study. A complete outline of the study design is depicted in Figure 3.1.

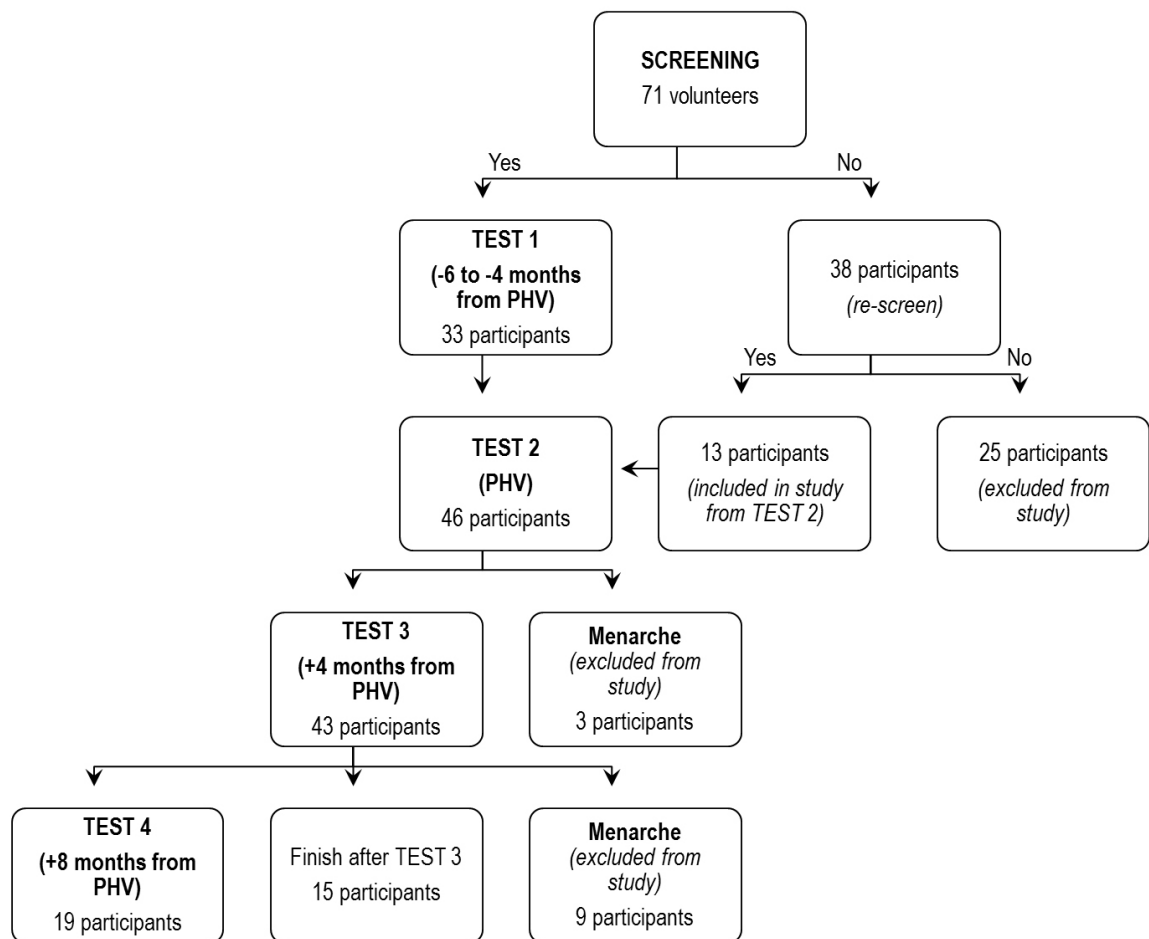


Figure 3.1: Participant selection protocol outlining the number of volunteers screened and re-screened, participant numbers during each testing session, as well as the attrition of participants due to menarche.

Due to cyclic fluctuations in hormones and knee laxity,⁵ participants who reached menarche (onset of menstruation) at any point during the 12-month testing period were excluded from the study at this point, such that all participants tested were pre-menarche and, because of participant availability, 15 participants did not complete

Test 4 (see Figure 3.1). Based on the method of Bach and Sharpe,²⁹ the sample size was shown to provide sufficient statistical power ($> 80\%$) to detect significant main effects at $p \leq 0.05$, when comparing the longitudinal changes in the dependent variables over time, when standing height was used as the outcome measure (standard deviation of the differences in measurements = 0.75 cm). All participants were recruited through schools from the Illawarra region, as well as through local newspaper advertisements in order to ensure the participants represented a general, pubescent female cohort, with minimal sample bias. The University of Wollongong Human Research Ethics Committee (HE08/281) approved all study procedures and the participants and their parents/guardians provided informed written and verbal consent before the girls participated in the study.

Experimental protocol

Participants were tested in the Biomechanics Research Laboratory up to four times over the 12-month period that encompassed their adolescent growth spurt (see Figure 3.1). The timing of each laboratory testing session was based around maturity offset, estimated using the regression equation described previously²⁷ (see Figure 3.2; Test 1: maturity offset = -6 to -4 months, Test 2: maturity offset = 0 months, Test 3: maturity offset = +4 months, Test 4: maturity offset = +8 months). During each laboratory test session, each participant's oestrogen levels, body mass, standing and sitting height, lower limb length, anterior knee joint laxity, lower limb flexibility and isokinetic strength of the dominant lower limb (defined as the landing limb each participant used when asked to perform a vertical jump, taking off from two legs and landing on one leg)³⁰ were measured. In addition, each participant's body mass, standing and sitting height, lower limb length (used to predict the timing of Test 2 and

retrospectively calculate height velocity), as well as their hamstring flexibility and isometric strength of the dominant limb (hereafter referred to the test limb) were tracked monthly in each participant's home. The chief investigator [CYW] performed all anthropometric, flexibility, knee laxity and strength measurements during both the laboratory and monthly tracking sessions, after confirming she was reliable (ICC > 0.9) in taking these measurements.

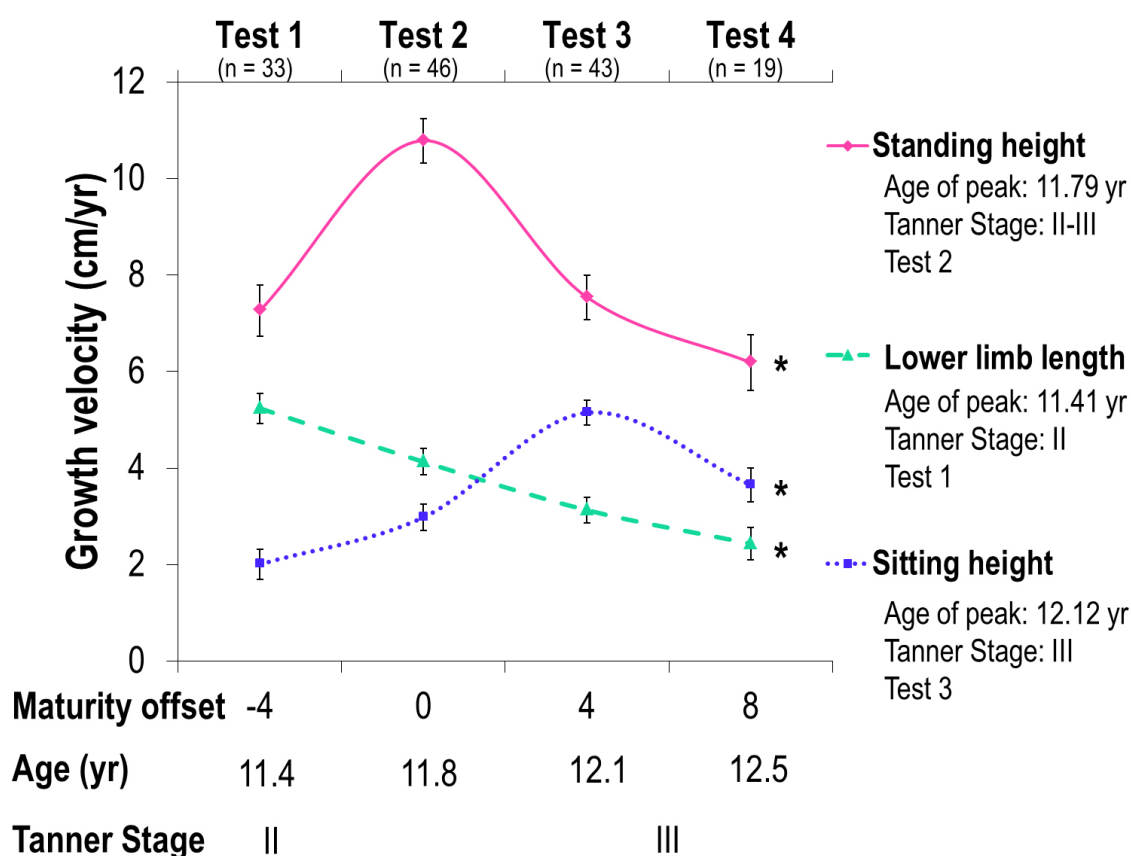


Figure 3.2: Timing of each of the four testing sessions based around maturity offset, estimated using a regression equation. Results are displayed as the means \pm SE for standing height, lower limb length and sitting height velocity over time, calculated retrospectively (height velocity data are attained from the 19 participants completing the 12-month study; * indicates a significant main effect of time on growth velocity; $p < 0.001$).

Anthropometric, flexibility and laxity measurements

During each laboratory and monthly tracking session, each participant's standing height, sitting height, lower limb length (Seca Corp, Hanover, MD, USA) and

body mass (A&D Personal Precision Scales, A&D Company Ltd., Tokyo, Japan) were quantified using the procedures described by Mirwald et al.²⁷ These values were then input into the regression equation to estimate maturity offset²⁷ (see Appendix B), as well as to track changes in these measurements throughout the adolescent growth spurt (see Table 3.1 for participant characteristics). As the stature measurements were crucial to the estimation of maturity offset,²⁷ the chief investigator [CYW] performed all measurements at approximately the same time of day for each participant (measurement error ± 0.4 cm). An estimate of height velocity was retrospectively calculated using the individual height data that were collected each month for the 19 participants who completed all four testing sessions, so as to obtain a height velocity value (cm/yr). This was calculated as the change in height two months prior to (this included the screening measurements when calculating height velocity at Test 1) and after each laboratory testing session divided by the change in time, multiplied by 12 months.

Table 3.1: Means \pm SE and *p*-values for the participant characteristics and the goniometric measures of hamstring, quadriceps and iliopsoas flexibility recorded during the four laboratory test sessions.

Variable	Test 1 (n = 33)	Test 2 (n = 46)	Test 3 (n = 43)	Test 4 (n = 19)	<i>p</i> -value
Standing height (cm)	149.7 \pm 0.8	152.7 \pm 0.8	155.2 \pm 0.8	157.9 \pm 0.8	<0.001
Lower limb length (cm)	70.6 \pm 0.6	72.4 \pm 0.6	73.5 \pm 0.6	74.7 \pm 0.6	<0.001
Body mass (kg)	40.1 \pm 0.8	42.2 \pm 0.8	44.2 \pm 0.8	46.7 \pm 0.8	<0.001
Age (yr)	11.4 \pm 0.1	11.8 \pm 0.1	12.1 \pm 0.1	12.5 \pm 0.1	<0.001
Tanner Stage	II	II-III	III	III-IV	<0.001
Hamstrings (°) ^a	23.7 \pm 2.3	25.3 \pm 2.1	24.1 \pm 2.2	21.4 \pm 2.5	0.295
Quadriceps (°)	68.0 \pm 1.6	64.2 \pm 1.4	64.4 \pm 1.4	66.2 \pm 2.0	0.112
Iliopsoas (°)	11.2 \pm 1.4	13.1 \pm 1.2	12.1 \pm 1.3	12.9 \pm 1.8	0.644

a. Note that a higher angle for hamstring flexibility indicates a decrease in flexibility, whereas a higher angle for quadriceps and iliopsoas flexibility indicates an increase in flexibility.

Goniometric measurements (Model 01135; Lafayette Instrument Co., Inc, USA; measurement error $\pm 2^\circ$) of knee (passive knee extension for the hamstrings and Modified Thomas Test for the quadriceps) and hip (Modified Thomas Test for

illiopsoas) joint ROM³¹ were recorded for each participant's test limb to represent changes in the flexibility of their hamstring, quadriceps and illiopsoas muscles over time (a higher angle for hamstring flexibility indicates a decrease in flexibility, whereas a higher angle for quadriceps and illiopsoas flexibility indicates an increase in flexibility). Hamstring flexibility (using the passive knee extension test)³¹ was also measured during the monthly tracking sessions to determine the month-to-month changes in hamstring muscle extensibility throughout the growth spurt.

Passive anterior knee laxity of each participant's test limb was measured using a Dynamic Cruciate Tester (DCT; Smith & Nephews Richards, Australia; measurement error ± 0.4 mm) and following the procedures of Steele et al.,³² which have been shown to be reliable (ICC > 0.9). In brief, the participants were seated in an adjustable chair, with their thigh supported, their knee flexed between 20-30° and their tibia in neutral rotation³² (see Figure 3.3). The ankle was firmly secured with a strain-gauged strap of the DCT, which was placed superior to the malleoli to limit vertical movement of the test limb, and the DCT tibial sensor was positioned on the participant's tibial tuberosity. In order to limit muscle guarding during testing, participants were encouraged to remain as relaxed as possible. This was enhanced by gently shaking the thigh and leg muscle bellies prior to each test, as well as by placing the contralateral leg in external rotation.³² Following 1-2 familiarisation trials, three passive anterior drawer tests were performed. Anterior tibial translation (mm) and the force applied by the participant's test limb against the ankle strap (N) were simultaneously recorded as force-displacement curves. For each participant, the anterior tibial displacement, recorded at a force value that was consistent throughout all testing sessions (80-100% of peak force; approximately 50-60 N), was averaged over the three trials to enable the changes in anterior knee

laxity over time to be compared.³² All knee laxity data were analysed at the completion of all testing sessions to limit any bias during future tests.

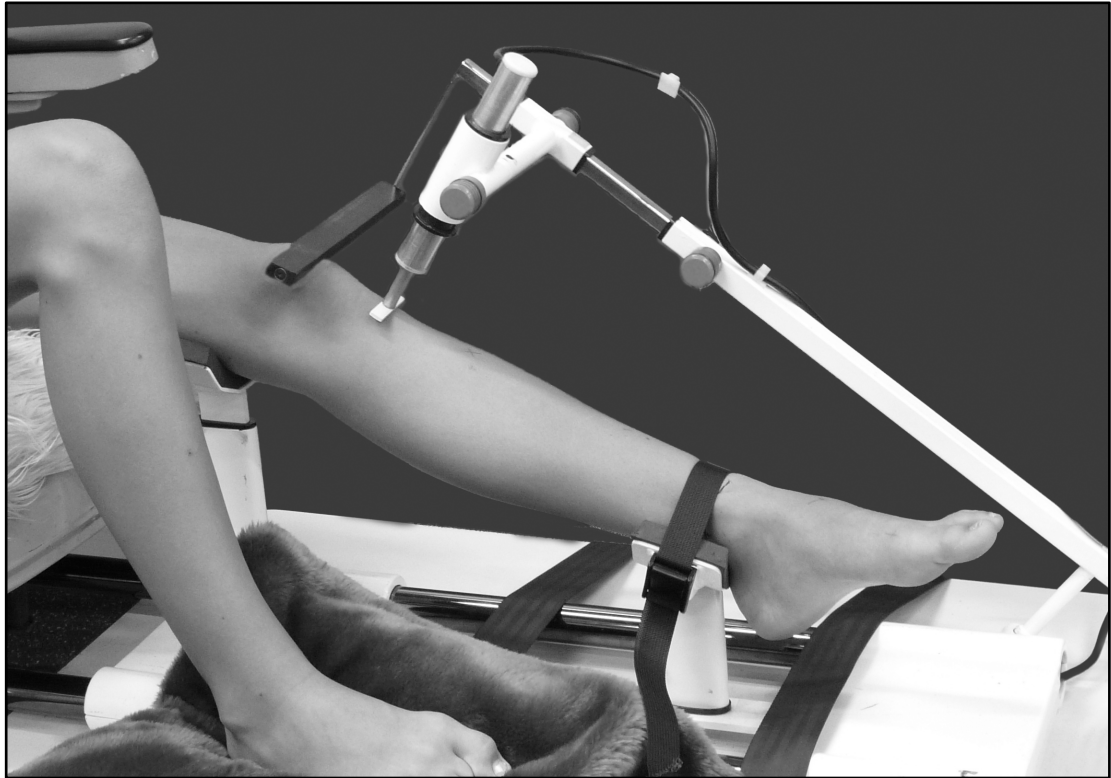


Figure 3.3: Dynamic Cruciate Tester set-up for anterior knee laxity assessments.

Isokinetic lower limb strength

After completing a standardised 5-10 minute warm-up on a cycle ergometer (Monark Model 818E, Sweden), each participant's hamstring and quadriceps muscle strength were assessed using an isokinetic dynamometer (KinCom, Chattanooga Inc., USA) following standardised procedures.³³ In brief, each participant was adequately familiarised with the strength testing procedures by performing a series of both concentric and eccentric quadriceps and hamstring muscle strength tests (with minimal effort), until each participant was confident with performing the tasks. Participants then performed four separate tests at 180°/s from 10-90° of knee flexion to assess concentric and eccentric hamstring and quadriceps muscle strength. An angular velocity of 180°/s

was selected to replicate the angular knee velocity displayed during landing, and which has been safely used previously with a similar cohort.³⁴ During each test, the lever arm moved back and forth for a total of six cycles. During the first two cycles, participants were asked to relax (0% effort), during cycles 3-4 participants were asked to exert 25% effort and during cycles 5-6 participants were asked to exert 100% effort. Participants performed one test for each of the strength measures (concentric hamstrings, eccentric hamstrings, concentric quadriceps and eccentric quadriceps), resulting in four tests performed by each participant. Each strength test was performed in a randomised order and the gravity corrected peak torque was recorded.³⁵ Participants were allowed adequate rest between each trial to reduce the effects of fatigue on peak torque values.

Isometric hamstring strength

Using modified, reliable procedures (ICC > 0.9, 95% confidence intervals),³⁶ month-to-month isometric hamstring strength was recorded by having participants sit with their knee and hip joints at 90° and a strap, connected to a tensiometer placed around their ankle, superior to the malleoli. With their arms crossed across their chest, participants were asked to pull their leg back (posteriorly) as hard as they could for 3 seconds and then to relax. Participants performed three trials, with 1-minute rest between each trial and the highest strength reading (kg) was recorded (measurement error ± 2 kg).

Salivary levels of oestrogen

Due to ethical constraints, as well as to reduce participant burden, estradiol (the most physiologically active form of oestrogen) concentration was measured by collecting saliva samples. One hour prior to each testing session, participants refrained

from eating. Participants rinsed their mouth thoroughly with water 10 minutes before each sample was collected, to minimise food particles compromising the results, and saliva samples were then collected employing the unstimulated passive drool method. Participants were instructed to allow saliva to pool in their mouth (this involved the participants ‘imagining’ their favourite food). Then, with their head tilted forward, participants allowed their saliva to passively move down a 5 cm-long straw and into a disposable tube (Eppendorf Inc; North America, USA; safe-lock tubes, 2.0 mL). Three 1 mL samples were collected over a 2 hour period and all samples were dated and stored at -20°C for later analysis.

For analysis, the saliva samples were completely thawed, vortexed and centrifuged at 1500 x g (at 3000 rpm) for 15 minutes at room temperature (approximately 22°C). Estradiol concentration was determined by enzyme immunoassay (EIA) using a high sensitivity EIA kit (Salivary 17 β -Estradiol EIA kit; Item no. 1-3702; Salimetrics., PA, USA; calibrator range: 1-32 pg/mL; serum correlation: 0.80). The assay plate (containing all standards, controls and unknowns) was then read in a plate reader (PowerWave x340, Bio-Tek., Victoria, Australia; 450 nm). Using data reduction software (GraphPad Prism 4; Version 4.03, 2005), the concentration of oestrogen in the controls and unknowns was determined through extrapolation of the standard curve.

Statistical analyses

Means and standard errors of the anthropometric, flexibility, anterior knee laxity, strength and oestrogen variables were calculated for each laboratory-based testing session, as well as the hamstring flexibility and strength measures for each monthly tracking session. A linear mixed model was used (repeated covariance type =

compound symmetry; correlated residuals within the random effects) to determine any significant ($p \leq 0.05$) main effects of time on the dependent variables, controlling for growth variables (height, body mass, lower limb length) as covariates (which were time dependent). The linear mixed model is a direct likelihood approach, which has been shown to be a suitable method for analysing longitudinal data with missing values, whereby the method assumes that data are missing at random.³⁷ Post-hoc comparisons were performed using a *t*-test with a Bonferroni adjustment. All statistical procedures were performed using SPSS (Version 20; SPSS Inc., Chicago, IL).

RESULTS

A significant main effect of time was displayed for the anthropometric variables (see Table 3.1), whereby standing height, lower limb length, body mass, chronological age and Tanner stage all significantly increased during each testing session throughout the 12 months. A significant main effect of time on standing height, lower limb length and sitting height growth velocity was also found (see Figure 3.2), whereby post-hoc analyses revealed that the increase in standing height was faster during Test 2 (at the time of PHV) compared to the other test sessions ($p < 0.001$). Post-hoc analyses also revealed that peak lower limb growth velocity was attained prior to PHV (Test 1; $p < 0.001$) and peak sitting height growth velocity, a reflection of torso growth, occurred after PHV (Test 3; $p < 0.003$).

Despite the rapid and differential timing of standing height, lower limb length and sitting height growth, there was no significant main effect of time on hamstring, quadriceps or iliopsoas flexibility over the four laboratory testing sessions (see Table 3.1). However, a significant ($p = 0.024$) effect of time on the month-to-month measures of hamstring flexibility was found (see Figure 3.4), whereby post-hoc

analyses revealed participants displayed significantly ($p = 0.001$) lower hamstring flexibility during Month 4 (1 month prior to PHV, Test 2) compared to Month 13 (Test 4).

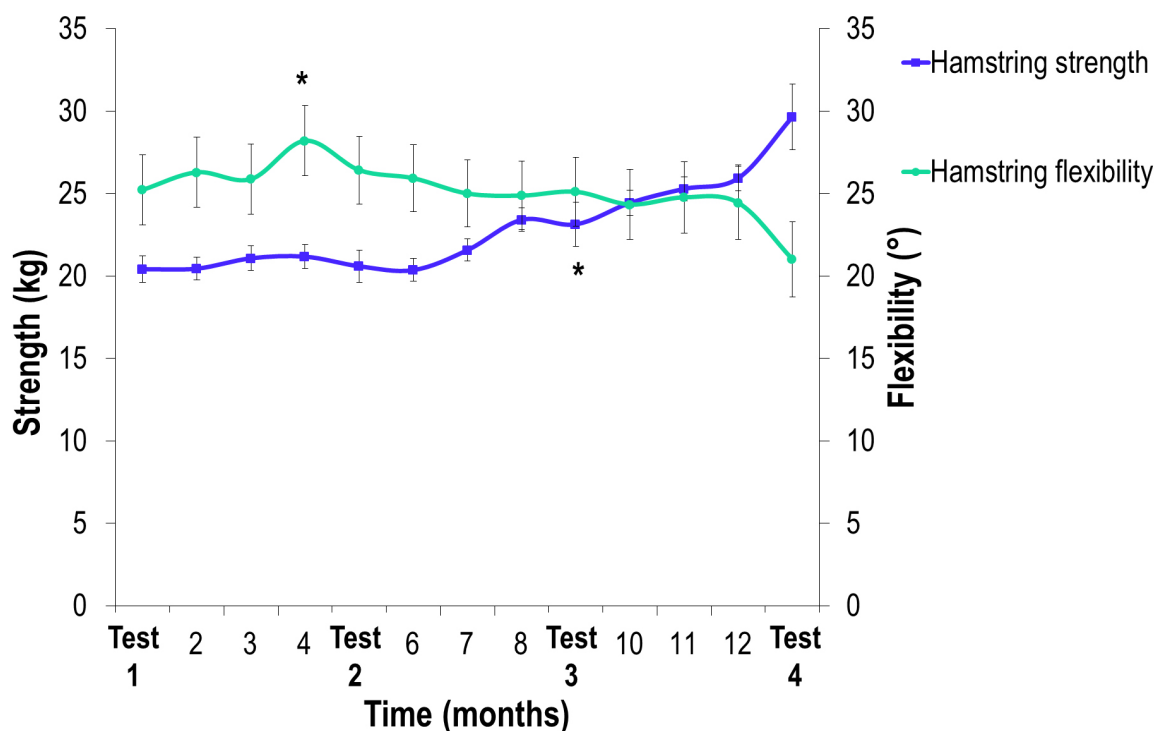


Figure 3.4: Means \pm SE for the month-to-month changes in hamstring flexibility and isometric hamstring muscle strength over 12 months (note that an increase in angle indicates a decrease in hamstring flexibility; * indicates a significant main effect of time on the dependent variable; $p < 0.05$).

Interestingly, there was no significant change in estradiol concentration throughout the 12 months ($p = 0.811$; see Figure 3.5). However, a significant effect of time on anterior knee laxity was found, whereby participants displayed an increase in knee laxity from Test 1 to 2 ($p = 0.001$) and Test 1 to 3 ($p = 0.029$).

Participants displayed no change in either concentric ($p = 0.539$) or eccentric ($p = 0.249$) hamstring muscle strength over time (see Figure 3.6). However, participants displayed a significant increase in concentric quadriceps muscle strength from Test 1 to 3 ($p = 0.011$), Test 1 to 4 ($p < 0.001$) and Test 2 to 4 ($p = 0.002$).

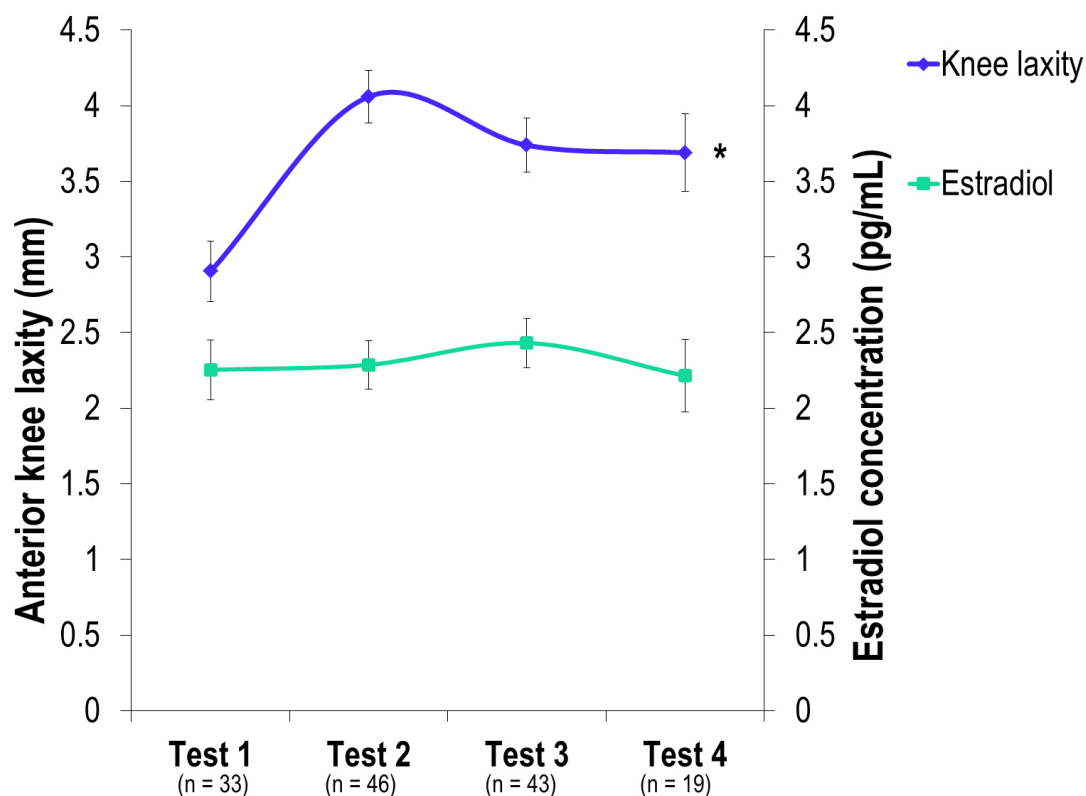


Figure 3.5: Means \pm SE for anterior knee laxity (mm) and estradiol concentration (pg/mL) over the four laboratory test sessions (* indicates a significant main effect of time on knee laxity; $p = 0.002$).

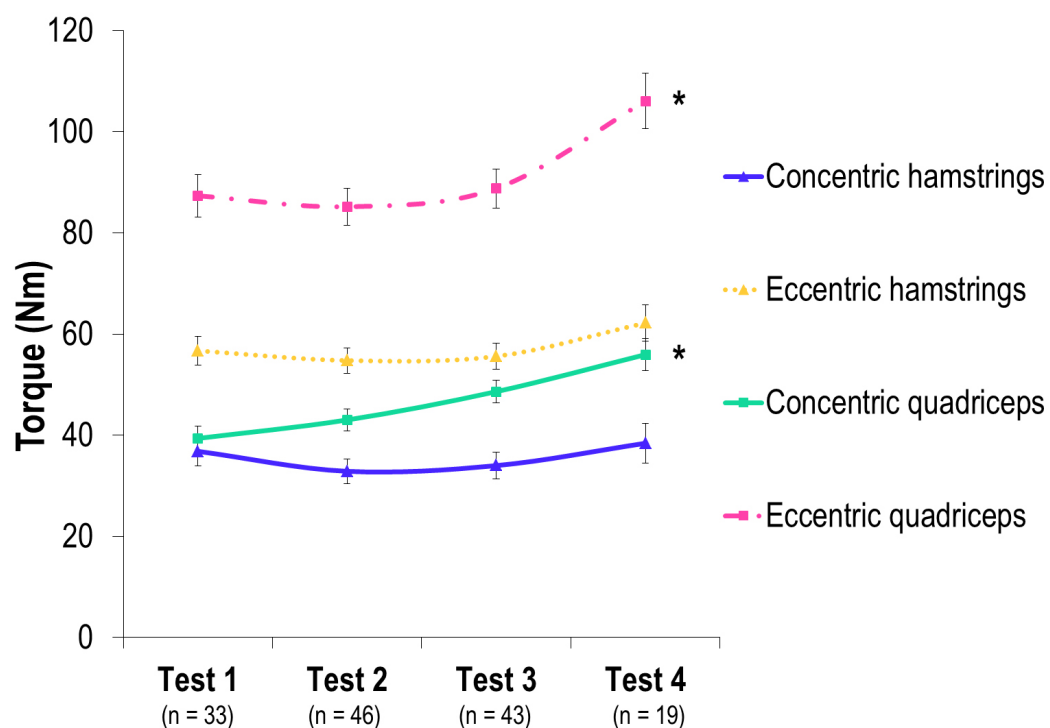


Figure 3.6: Means \pm SE for the concentric and eccentric hamstring and quadriceps muscle torque (Nm) over the four laboratory test sessions (* indicates a significant main effect of time on the strength variable; $p < 0.05$).

Participants also displayed significantly greater eccentric quadriceps muscle strength at Test 4 compared to Test 1 ($p = 0.017$), Test 2 ($p = 0.003$) and Test 3 ($p = 0.024$). Interestingly, a significant ($p < 0.001$) effect of time on the month-to-month changes in isometric hamstring muscle strength was also found (see Figure 3.4), such that post-hoc analyses revealed that participants displayed a significant ($p < 0.023$) increase in hamstring strength from Month 10 (1 month after Test 3) to Month 13 (Test 4).

DISCUSSION

It has been speculated that the rapid growth, as well as the musculoskeletal and hormonal changes that occur during puberty, may be factors contributing to the reported increased ACL injury risk in girls at this time.³ This study investigated the longitudinal changes in anthropometry, oestrogen and knee laxity, as well as lower limb strength and flexibility during the adolescent growth spurt in girls, in order to provide a greater understanding of changes in these variables during this time. As hypothesised, rapid changes in height, flexibility and knee laxity occurred throughout the growth spurt, which are detailed below.

As would be expected during a growth spurt, the participants displayed a significant increase in all growth parameters over time, including height, lower limb length and body mass, as well as chronological age and Tanner stage (see Table 3.1). Participants also experienced different rates of growth in standing and sitting height, as well as lower limb length throughout the 12 months (see Figure 3.2). This compares to previously reported height velocity curves in pubescent girls in terms of both the magnitude and timing of each peak growth velocity,²⁷ offering further confirmation of current knowledge that peak lower limb growth occurs prior to the time of PHV,

whereas peak torso growth (sitting height) occurs after PHV. Furthermore, the PHV attained by participants is comparable to values reported in the literature of approximately 8-10 cm/yr.¹¹ The Tanner stage (II-III) of the participants at the time of PHV is also comparable to previously reported values.^{27, 38}

Bones grow faster than the developing musculature, and so it may be assumed that the rapid increase in lower limb length and height velocity at the time of Test 1 and 2 would be accompanied by an associated decrease in lower limb flexibility during this time,²⁶ as has been reported previously.²¹⁻²³ When the month-to-month changes in hamstring flexibility were analysed, a significant decrease in hamstring flexibility was noted just prior to the time of PHV (Test 2), around the time of peak lower limb length growth (see Figure 3.2). This finding is comparable to the results of Loko et al.²² and whilst further research is warranted to confirm this notion, may suggest that rapid growth of the lower limbs just before PHV contributes to a reduction in hamstring flexibility and potentially increased injury risk.²⁵

In contrast to previous research,²¹⁻²⁴ the present study found no associated changes in hamstring, quadriceps or iliopsoas flexibility throughout the growth spurt when measured in the laboratory every 4 months, despite significantly changing height velocity throughout the 12 months. Heras-Yague et al.²¹ measured the changes in maximal trunk flexion in girls twice annually for 3 years, reporting a decrease around the time of PHV and an increase in flexibility after PHV. Although involving a larger cohort than the present study (453 girls aged between 10-13 years), it is thought that only two measurements per year cannot accurately characterise the changes in flexibility, particularly when it is not aligned with changes in lower limb and sitting height growth. In addition, many studies²¹⁻²³ assess trunk flexion flexibility as 'touching the fingertips to the floor' or using the sit-and-reach test. Based on the anthropometric

results from the present study, increases in trunk flexion, like those displayed by Heras-Yague et al.²¹ after PHV, may not be due to improved flexibility or ROM at all, but merely due to an increase in torso length (sitting height) and a slowing down of lower limb growth (see Figure 3.2). Unlike these previous studies, we assessed the participant's flexibility using joint ROM tests, making comparisons to current literature difficult. However, as no changes in hamstring, quadriceps or iliopsoas muscle flexibility were noted over time when measured every 4 months, whereas significant changes in hamstring flexibility were found when assessed monthly, we recommend that regular monitoring of girls during their growth spurt is required to detect changes in lower limb flexibility and potential 'at risk' times during the adolescent growth spurt.

Growth in length of the lower limbs of approximately 5 cm/yr leading up to, and around the time of PHV (Test 1 and 2), results in changes in the inertial properties of these segments.¹³ This requires an analogous increase in lower limb muscular strength, particularly around the time of Test 1 (peak lower limb growth velocity), in order to effectively accelerate and decelerate the limbs for given movements, such as landing.¹³ The importance of the quadriceps and hamstring muscles during dynamic landing movements has been highlighted, particularly with respect to stabilising the knee joint and protecting the ACL.³ Similar to the results reported by Barber-Westin et al.,²⁰ participants in the present study displayed a significant increase in isokinetic (concentric and eccentric) quadriceps muscle strength after PHV, with no apparent acceleration in the development of isokinetic (concentric and eccentric) hamstring muscle strength over time. This demonstrates a lag in development of hamstring muscle strength relative to quadriceps muscle strength over time, particularly with respect to the rapidly growing lower limbs around the time of Test 1. Further research is recommended to determine

whether this lag in hamstring strength development negatively affects how girls perform dynamic landing movements and, in turn, their risk of ACL injury.

Heitz et al.⁵ reported an association between increased anterior knee laxity and peak rises in both oestrogen and progesterone throughout the menstrual cycle. This suggests that increases in oestrogen may contribute to greater ligament laxity which, in turn, is thought to decrease knee joint stability³⁹ and ultimately, increases the potential for ACL injury. Interestingly, participants in the present study displayed a significant increase in anterior knee laxity from the time of PHV, which is comparable to the results of previous studies,^{6,9} but with no associated increase in estradiol concentration (see Figure 3.5). Whilst the estradiol concentration values in the present study are significantly lower than the concentrations reported previously,⁵ these previous values were of serum measurements of regular menstruating women. In fact, the reported estradiol concentrations (2-4 pg/mL) in the present study are comparable to values reported in a similar non-menstruating pubescent female population.² Therefore, we speculate the longitudinal changes in lower limb flexibility, strength and laxity displayed in the present study may be attributed to factors outside of oestrogen influences. Further research is warranted, however, to determine whether the increase in knee laxity displayed by girls from the time of PHV in the present study, combined with a lag in development of hamstring relative to quadriceps strength, decreases knee joint stability during dynamic landing tasks,³⁹ potentially placing girls at an increased risk of non-contact ACL injuries during sport.

Whilst this study provides greater insight into the musculoskeletal and oestrogen changes during puberty, particularly when measured longitudinally, limitations of the study are acknowledged. Despite our findings being consistent with previous studies of non-menstruating girls, we propose that hormonal measurements every 4 months may

not have been sensitive enough to detect subtle changes in oestrogen during the growth spurt in girls. Therefore, research that investigates the changes in other hormones associated with puberty, such as testosterone and progesterone, together with oestrogen, measured on a more regular basis (i.e. daily), as well as through other non-invasive methods such as urine, would provide further insight into the effects of hormones during the adolescent growth spurt. Furthermore, in the present study it was assumed that peak lower limb growth occurred at the time of Test 1. We acknowledge, however, that this may not be the actual peak and thus recommend further investigation to determine the precise timing of peak lower limb growth. Whilst it is acknowledged that the best indicator of biological age is through x-rays to calculate skeletal age, due to ethical constraints placed on the present study, use of skeletal age was not possible. Instead, Tanner staging and maturity offset were used to characterise pubertal and biological age. In addition, whilst the statistical method used in the present study was able to account for missing data, it is acknowledged that the discrepancy in the number of participants during each testing session is a study limitation. Finally, the lack of physical activity data of each participant presents as a limitation as seasonal changes in sporting activity may have contributed to an increase in variability of the results, suggesting the need for future studies to include these variables as covariates.

Overall, it was found that from the time of PHV, participants displayed significantly increased anterior knee laxity, accompanied by a significant increase in isokinetic quadriceps muscle strength over time, with no accompanying increase in isokinetic hamstring muscle strength or oestrogen concentration. A significant decrease in hamstring flexibility just prior to PHV, around the time of peak lower limb growth velocity, was also evident. We speculate that this combination of changes during the adolescent growth spurt in girls might contribute to a decrease in their knee joint

stability during landing tasks, potentially increasing ACL injury risk at this time of rapid height and lower limb growth. Therefore, further research is recommended to determine whether these musculoskeletal and growth variables affect the way girls land at critical stages of the adolescent growth spurt.

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Chapter 4

Does insufficient hamstring strength compromise landing technique in pubescent girls?

This chapter is an amended version of the manuscript: Wild CY, Steele JR, Munro BJ. Insufficient hamstring strength compromises landing technique in adolescent girls. *Medicine & Science in Sports & Exercise*. In review, re-submitted for publication, July 2012.

ABSTRACT

Females sustain more ACL ruptures than males and this gender disparity is apparent from the pubertal onset. Although the hamstring muscles play a vital role in ACL protection during landing by restraining anterior tibial motion relative to the femur, it is unknown whether hamstring muscle strength affects landing biomechanics during a functional movement. **Purpose:** This study aimed to determine whether pubescent girls with lower hamstring muscle strength displayed different lower limb biomechanics when landing from a leap compared to girls with higher hamstring muscle strength. **Methods:** Thirty-three healthy girls, aged 10-13 years, in Tanner Stage II (pubertal onset) and 4-6 months from their peak height velocity were recruited. Concentric and eccentric isokinetic strength of the hamstring and quadriceps muscles were assessed. Based on peak concentric hamstring torque, participants were divided into a lower (peak torque < 45 Nm) and higher (peak torque > 60 Nm) strength group. Participants performed a functional landing movement, during which ground reaction forces (GRF; 1,000 Hz), lower limb electromyography (EMG; 1,000 Hz) and kinematic data (100 Hz) were collected. **Results:** Girls with lower hamstring strength displayed significantly ($p < 0.05$) greater knee abduction alignment, reduced hip abduction moments and

greater estimated ACL loading at the time of the peak anteroposterior GRF compared to their stronger counterparts. **Conclusion:** Girls with reduced hamstring muscle strength appear to have a decreased capacity to control lower limb frontal plane alignment. This reduced capacity appears to contribute to increased estimated ACL loading and, in turn, increased potential for injury.

INTRODUCTION

Acute rupture of the ACL is a common and devastating knee injury, 70% of which are sport-related.¹ Within the same sport, females are 2-8 times more likely to rupture their ACL through non-contact mechanisms compared to their male counterparts.² This gender disparity in ACL rupture rate is apparent from the onset of puberty,³ a time of life which is accompanied by a large influx of hormones in combination with the adolescent growth spurt.⁴ The rapid and sizeable increases in height and limb length⁵ (see Figure 3.2), combined with the large influx of hormones during puberty,⁴ could play a role in the aetiology of non-contact ACL ruptures in this population.

A common non-contact ACL injury mechanism occurs when athletes rapidly decelerate when landing from a jump, particularly during landings that involve a horizontal approach.⁶ During such landings, an anterior drawer force is imparted to the tibia as the quadriceps muscles are contracted in an attempt to prevent the knee from collapsing upon initial contact with the ground. This quadriceps contraction exacerbates anterior tibial translation, which the ACL attempts to restrain.⁷ In addition to anterior tibial translation, the ACL is also strained during abduction and rotation of the knee, which are also commonly observed during landing tasks.^{6, 8, 9}

As antagonists to the quadriceps muscles, the hamstring muscles play a highly important role in stabilising the knee joint during landing tasks.¹⁰ Due to the posterior and superior attachment of the hamstring muscles on the tibia and fibula, contracting the hamstring muscles during landing can impart an increasing posteriorly directed force on the proximal tibia as the knee flexes, thereby acting as a synergist to the ACL during anterior tibial translation.⁷ Whilst dependent on knee and hip alignment, the ability of the hamstring muscles to cause medial and lateral rotation at the knee,¹¹ as well as control coronal plane knee motion,¹² highlights the potential of the hamstring muscles to also protect the ACL against high rotational and abduction strain. A significant reduction in coronal plane knee moments experienced during landing have been reported in females following a training intervention, whereby significant increases in hamstring muscle strength were observed.¹⁰ This confirms the important role of the hamstring muscles in protecting the knee, as well as the ACL, against potentially high external abduction loads during landing.¹⁰ Interestingly, adult males are suggested to utilise their hamstring muscles more effectively to protect the ACL compared to females, contracting their muscles so that the peak hamstring muscle activity better coincides with the high tibiofemoral shear forces experienced during landing.⁷ Therefore, whilst the potential protective role of the hamstring muscles during landing in adults is understood,^{7, 10, 13} it is unknown whether girls are able to effectively use their hamstring muscles to protect their ACL during their growth spurt or whether changes in muscle strength during puberty compromise landing technique.

Ahmad et al.¹⁴ collected peak isometric hamstring and quadriceps muscle strength data using a handheld dynamometer and reported that mature girls (2 years post-menses) displayed lower hamstring-to-quadriceps ratios (0.51) compared to their mature male counterparts (0.69) and compared to prepubescent males and females (0.63

and 0.58, respectively). Furthermore, although the mechanism is not well understood, lower hamstring-to-quadriceps ratios have been shown to contribute to greater lower limb valgus and tibial rotation angles during dynamic movements, which can also increase loading of the ACL.¹⁵ Recently, it has been shown that lower reported hamstring-to-quadriceps ratios in ACL injured females compared to male controls is due to lower hamstring muscle strength, with no differences in quadriceps strength.¹⁶ This emphasises the need to further determine whether changes in hamstring muscle strength during puberty alter landing mechanics of pubescent girls, ultimately placing them at an increased risk of ACL injury.

Interestingly, previous research has demonstrated that boys experience a defined ‘spurt’ in muscle strength development during puberty, particularly evident in hamstring muscle strength, although this strength spurt is not apparent in girls.^{8, 14, 17} The rapid growth of the lower limbs during puberty results in an increase in the inertial properties of the lower limb segments.¹⁸ This, in turn, requires greater muscular torque to control the limbs during dynamic landing movements. We speculate that this lack of a strength spurt in girls during puberty (see Figure 3.6), paired with lower hamstring-to-quadriceps ratios, may provide further explanation for the increased risk of non-contact ACL ruptures in adolescent females.

Despite the fact that pubescent girls display lower hamstring-to-quadriceps ratios during puberty without a defined strength development spurt, it is unknown whether hamstring strength affects landing mechanics in girls from the onset of puberty. Furthermore, most previous studies in this field have investigated the landing technique of young girls performing bilateral drop-landing maneuvers.^{8, 15} Given that the ACL primarily restrains anterior and thus horizontal tibial translation, a movement that has a horizontal approach to the landing is more ecologically valid compared to drop-landings

when developing implications for ACL injury mechanisms in females. Therefore, the purpose of this study was to determine whether pubescent girls with lower hamstring muscle strength displayed different lower limb biomechanics when landing after performing a horizontal leap movement compared to girls with higher hamstring muscle strength. It was hypothesised that girls with lower hamstring strength would display significantly lower hamstring-to-quadriceps ratios, as well as significantly different lower limb kinematics and kinetics, including higher estimated ACL loading and altered muscle activation patterns, during landing compared to girls with higher hamstring strength.

METHODS

Participants

Seventy-one healthy, female volunteers aged between 10-13 years were initially screened for their Tanner stage of pubertal development,¹⁹ as well as the estimated time they were from reaching their PHV (referred to as maturity offset), to determine pubertal onset.⁴ Each girl's Tanner stage was self-assessed using modified Tanner stage diagrams¹⁹ (see Appendix A) and maturity offset was estimated using a sex-specific multiple regression equation⁵ (see Appendix B).

Thirty-three girls satisfied the inclusion criteria (pubertal onset;²⁰ Tanner Stage II of pubic hair development and maturity offset = -6 to -4 months) and were recruited as participants. Girls were excluded if they did not satisfy the developmental inclusion criteria, had a lower limb injury that prevented them from participating in physical activity or sport, or had begun menstruating. The University of Wollongong Human Research Ethics Committee (HE08/281) approved all study procedures and the

participants and their parents/guardians provided informed written and verbal consent prior to the girls participating in the study.

Isokinetic lower limb strength

After completing a standardised 5-10 minute warm-up on a cycle ergometer (Monark Model 818E, Sweden), each participant's hamstring and quadriceps strength was assessed using an isokinetic dynamometer (KinCom, Chattanooga Inc., USA), following standardised procedures^{21, 22} (see Chapter 3). Participants performed one test for each of the strength measures (concentric hamstrings, eccentric hamstrings, concentric quadriceps and eccentric quadriceps) in a randomised order. The peak torque, as well as the torque later calculated to correspond to the knee angle displayed at the time of the peak anteroposterior ground reaction force (GRF) during the landing task, were recorded. Hamstring-to-quadriceps ratios were then calculated for each participant, including the peak concentric ratios ($H_{con}:Q_{con}$) for comparison to the literature, and functional ratios ($H_{con}:Q_{ecc}$) corresponding to the knee angles displayed at the time that the peak anteroposterior GRF was generated during landing.²¹ Participants were allowed adequate rest between each trial to reduce the effects of fatigue on peak torque values.

Landing task

Following preparation, adequate jump task familiarisation was carried-out. Participants then performed a horizontal leap whereby they jumped as far forward as they were able, taking off from two-legs and landing on the force platform with their test limb only (see Figure 4.1). During the horizontal leap task, each participant placed their arms across their chest, to reduce any effect that arm motion had on landing

technique²³ and focused on a picture on the wall to prevent ‘targeting’ of the force platform. Participants performed 5-7 successful trials (landing within the confines of the force platform) of the horizontal leap movement and fatigue was avoided by providing ample rest periods when required.



Figure 4.1: Horizontal leap movement.

Data collection and analysis

During the horizontal leap movement, the three orthogonal components of the GRF generated by each participant upon landing were measured (1,000 Hz) using a calibrated multichannel force platform (Type 9281B; Kistler, Switzerland; 600 mm x 400 mm) embedded in the laboratory floor, and amplified using a Kistler Multichannel charge amplifier (Type 9865A; Kistler, Switzerland). The raw GRF data were filtered using a fourth-order zero-phase-shift Butterworth digital low-pass filter ($f_c = 100$ Hz) before calculating the timing of initial contact (IC), as well as the peak vertical and anteroposterior GRF.

The three-dimensional motion (100 Hz) of each participant's dominant lower limb during the landing task was recorded using an OptoTRAK 3020 motion analysis system (Northern Digital Inc, Canada). Eighteen infrared-emitting diodes were adhered to 18 anatomical landmarks (5th and 1st metatarsal head, intermediate cuneiform, lateral calcaneus, lateral and medial malleoli, 25% and 75% of anterior shank, lateral and

medial femoral condyles, 25% and 75% of anterior thigh, right and left greater trochanters, right and left anterior superior iliac spines and right and left iliac crests) on each participant's test limb. The infrared-emitting diodes were adhered to the participant's skin using double-sided toupee tape (Creative Hair Products, Australia) and 3MTM transpore plastic tape (Livingstone International Pty Ltd, Australia).

A three-dimensional model of the foot, shank, thigh and pelvis segments of the dominant lower limb was created in Visual3D (Version 4, C-Motion Inc, USA) from a standing calibration file of each participant and based on each participant's inertial properties.²⁴ The three-dimensional ankle, knee and hip joint angles (whereby positive angles were defined as dorsiflexion, eversion and forefoot abduction for the ankle; and flexion, abduction and external rotation for the knee and hip), were then calculated at the times of IC, peak vertical GRF and peak anteroposterior GRF to determine lower limb kinematics during the impact phase of landing.

The raw kinematic, GRF, free moment and centre of pressure data were then filtered using a fourth-order zero-phase-shift Butterworth digital low-pass filter ($f_c = 14$ Hz; determined using residual analysis),²⁵ prior to calculating the lower limb kinematics and joint moments.²⁶ Three-dimensional ankle, knee and hip internal joint moments at the time of IC, peak vertical GRF and peak anteroposterior GRF were calculated using an inverse dynamics approach²⁵ and normalised to each participant's body mass. Positive moments were defined as dorsiflexion, eversion and forefoot abduction for the ankle; extension, abduction and external rotation for the knee; and flexion, abduction and external rotation for the hip. An estimation of ACL force during landing was calculated using a validated two-dimensional knee joint model.⁹ The relative contributions of the hamstring and quadriceps muscle forces were calculated using equations for tendon orientation as a function of knee joint angle.²⁷ These

contributions were added to the resultant anterior-posterior knee joint load to obtain an estimate of the anterior drawer force. Finally, ACL forces were estimated by dividing the anterior drawer force by the line of action of the ACL, also calculated as a function of knee angle.²⁷ The magnitude and timing of the peak ACL forces (F_{ACL}), normalised to body weight, as well as the magnitude of F_{ACL} at the time of the peak anteroposterior GRF, were calculated to characterise potential ACL loading during landing.

Activity of medial gastrocnemius (MG), tibialis anterior (TA), vastus medialis (VM), rectus femoris (RF), semitendinosus (ST) and biceps femoris (BF) of each participant's dominant lower limb were recorded using bipolar Ag-AgCl surface electrodes (2 cm inter-electrode spacing; Blue Sensor Type M-OO-S, Medico test, Denmark) following standard preparation.²⁸ A reference electrode was placed on the tibial tuberosity of the dominant lower limb. Electromyographic signals from the electrodes were relayed to a Telemetry transmitter (Noraxon, USA; 1,000 Hz; bandwidth 16-500 Hz) and then to a Telemetry receiver via an antenna. The EMG data were then analysed using a custom-written LabVIEW software program (EMGAnalyser V3, 2011). Raw signals were firstly inspected to discard trials contaminated with noise or movement artefact. Following signal offset removal, raw EMG signals were filtered using a zero-phase shift fourth-order high-pass Butterworth filter ($f_c = 15$ Hz) full-wave rectified and filtered using a low pass Butterworth filter ($f_c = 20$ Hz), in order to obtain linear envelopes (mV) closely representing the muscle tension curves.^{7, 25} The filtered EMG signals were visually inspected, using a threshold detector of 8%, to determine the timing of muscle onsets and peak activity relative to IC. The kinematic, GRF and EMG data were time synchronised during data collection using First Principles software (Version 1.2.2; Northern Digital, Canada).

Statistical analyses

In order to assess whether hamstring muscle strength affected landing biomechanics, the 33 participants were divided into a lower hamstring strength group (peak torque < 45 Nm; $n = 11$) and higher hamstring strength group (peak torque > 60 Nm; $n = 11$) based on the frequency distribution of the peak concentric hamstring muscle strength results (see Figure 4.2).

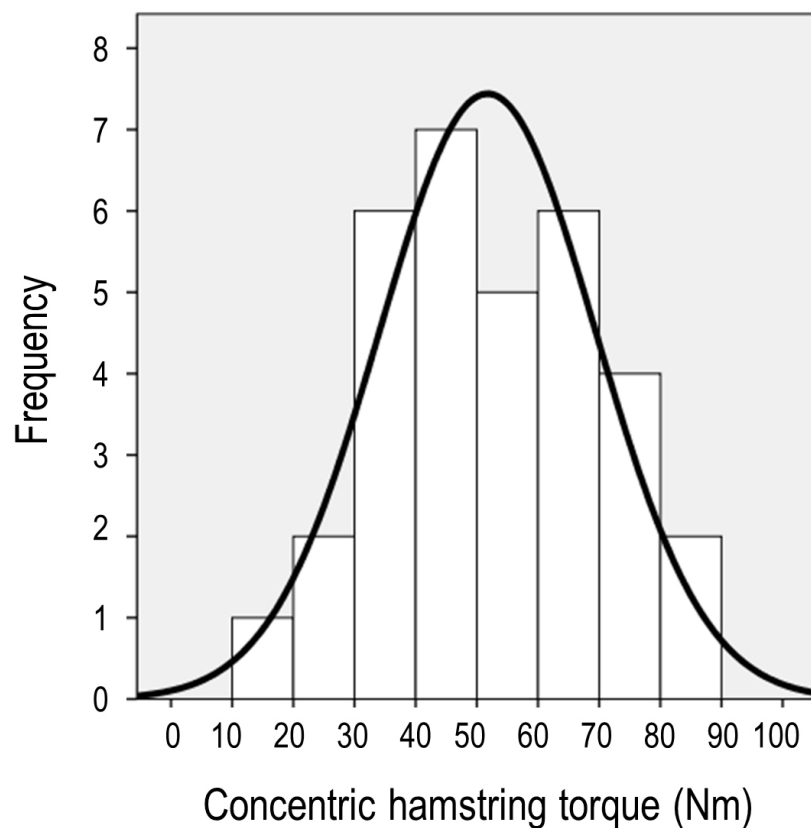


Figure 4.2: Frequency distribution of the concentric hamstring muscle torque (Nm) for all 33 participants.

The 11 participants whose peak hamstring torque was measured to be between 45 Nm and 60 Nm were removed from further analysis to ensure a significant between-group difference in hamstring muscle strength ($p = 0.012$; see Table 4.1 for participant characteristics). Jump distance during the experimental landing task was similar between the two participant groups ($p = 0.840$; 1.22 ± 0.12 m and 1.20 ± 0.19 m for the

lower and higher strength groups, respectively). The sample size provided sufficient statistical power ($> 80\%$) to detect significant main effects at $p \leq 0.05$ between the two groups when comparing lower limb muscle strength and landing biomechanics.²⁹

Table 4.1: Participant characteristics, as well as the peak absolute and normalised concentric hamstring and quadriceps muscle torques, for the lower ($n = 11$) and higher ($n = 11$) concentric hamstring strength groups (means \pm SD).

Variable	Lower strength	Higher strength	<i>p</i> -value
Height (cm)	150.0 \pm 4.7	150.5 \pm 6.4	0.850
Leg length (cm)	71.3 \pm 3.7	70.7 \pm 4.7	0.746
Mass (kg)	36.4 \pm 2.4	43.7 \pm 4.6	<0.001
Tanner stage	II	II	0.614
Concentric hamstring torque (Nm)	42.5 \pm 8.2	70.8 \pm 9.1	< 0.001
Concentric quadriceps torque (Nm)	85.4 \pm 12.9	88.3 \pm 26.2	0.741
Normalised concentric hamstring torque (Nm/kg)	1.0 \pm 0.1	1.8 \pm 0.2	< 0.001
Normalised concentric quadriceps torque (Nm/kg)	2.3 \pm 0.4	2.1 \pm 0.6	0.203

Means and standard deviations of the lower limb isokinetic strength, kinematics, moments, ACL force and EMG variables were calculated for the lower and higher hamstring muscle strength groups. Independent samples *t*-tests were then applied to the data to determine whether there were any significant ($p \leq 0.05$) differences in the lower limb landing biomechanics displayed by the lower hamstring muscle strength group relative to their higher hamstring strength counterparts during the horizontal leap movement. Although multiple comparisons were made, no adjustment to the alpha level was deemed necessary given the exploratory nature of the present study and because such adjustments may increase the likelihood of Type II errors.³⁰ All statistical procedures were validated through the University of Wollongong Statistical Consulting Service and conducted using SPSS (Version 17; SPSS Inc., Chicago, IL).

RESULTS

Hamstring-to-quadriceps ratios

The hamstring-to-quadriceps ratios calculated for the two hamstring strength groups are displayed in Figure 4.3. Overall, participants with lower hamstring strength displayed significantly lower $H_{con}:Q_{con}$ ($p = 0.011$) and $H_{con}:Q_{ecc}$ ($p = 0.010$) ratios, compared to the higher hamstring strength group.

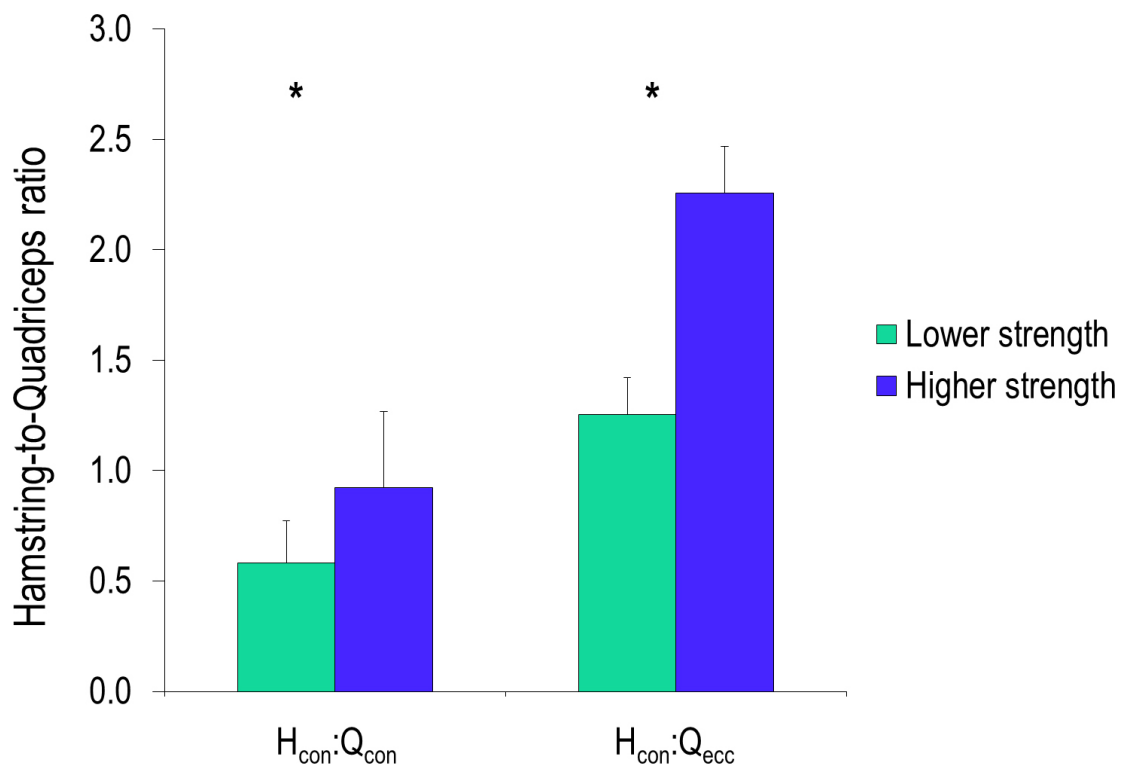


Figure 4.3: Means \pm SD for the hamstring-to-quadriceps ratios, including peak concentric ($H_{con}:Q_{con}$) and functional (corresponding to knee angles during landing; $H_{con}:Q_{ecc}$) ratios, for the lower and higher concentric hamstring strength groups (* indicates a significant between-group difference at $p \leq 0.05$).

Kinematic results and joint moments

Although no between-group differences were noted for the ankle kinematics or moments (see Figure 4.4a), the lower hamstring strength group displayed significantly lower hip extension moments at the time of IC ($p = 0.014$; Figure 4.4c). In the frontal plane, girls with lower hamstring strength displayed significantly greater knee abduction

at the time of the peak vertical ($p = 0.050$) and peak anteroposterior ($p = 0.030$) GRF. Whilst no between-group differences were evident for knee abduction moments, girls with lower hamstring strength displayed significantly ($p = 0.050$) lower hip abduction moments at the time of peak vertical GRF (see Figure 4.4).

A between-group difference ($p = 0.041$) was displayed for transverse plane biomechanics, such that girls with lower hamstring strength displayed knee internal rotation at the time of the peak anteroposterior GRF, whereas girls with higher hamstring strength displayed knee external rotation at this same point in time. This was also the case at the time of the peak vertical GRF, although this difference was not significant ($p = 0.062$). Girls with lower hamstring strength displayed significantly ($p = 0.001$) lower knee external rotation moments at the time of IC compared to their higher hamstring strength counterparts. A significant between-group difference was also evident for hip external rotation at the time of the peak anteroposterior GRF ($p = 0.037$), as well as hip external rotation moments at the time of the peak vertical GRF ($p = 0.050$; see Figure 4.4c).

Estimated ACL loading

No between-group differences were noted for timing of F_{ACL} (59.6 ± 13.7 ms and 65.8 ± 12.3 ms for the lower and higher hamstring strength groups, respectively; $p = 0.315$), or the magnitude of the normalised F_{ACL} at the time of the peak vertical GRF (0.97 ± 1.21 BW and 1.14 ± 0.65 BW for the lower and higher hamstring strength groups, respectively; $p = 0.702$). However, girls with lower hamstring strength displayed significantly ($p = 0.034$) greater normalised F_{ACL} at the time of the peak anteroposterior GRF (3.0 ± 1.3 BW) compared to girls with higher hamstring strength (1.7 ± 0.9 BW).

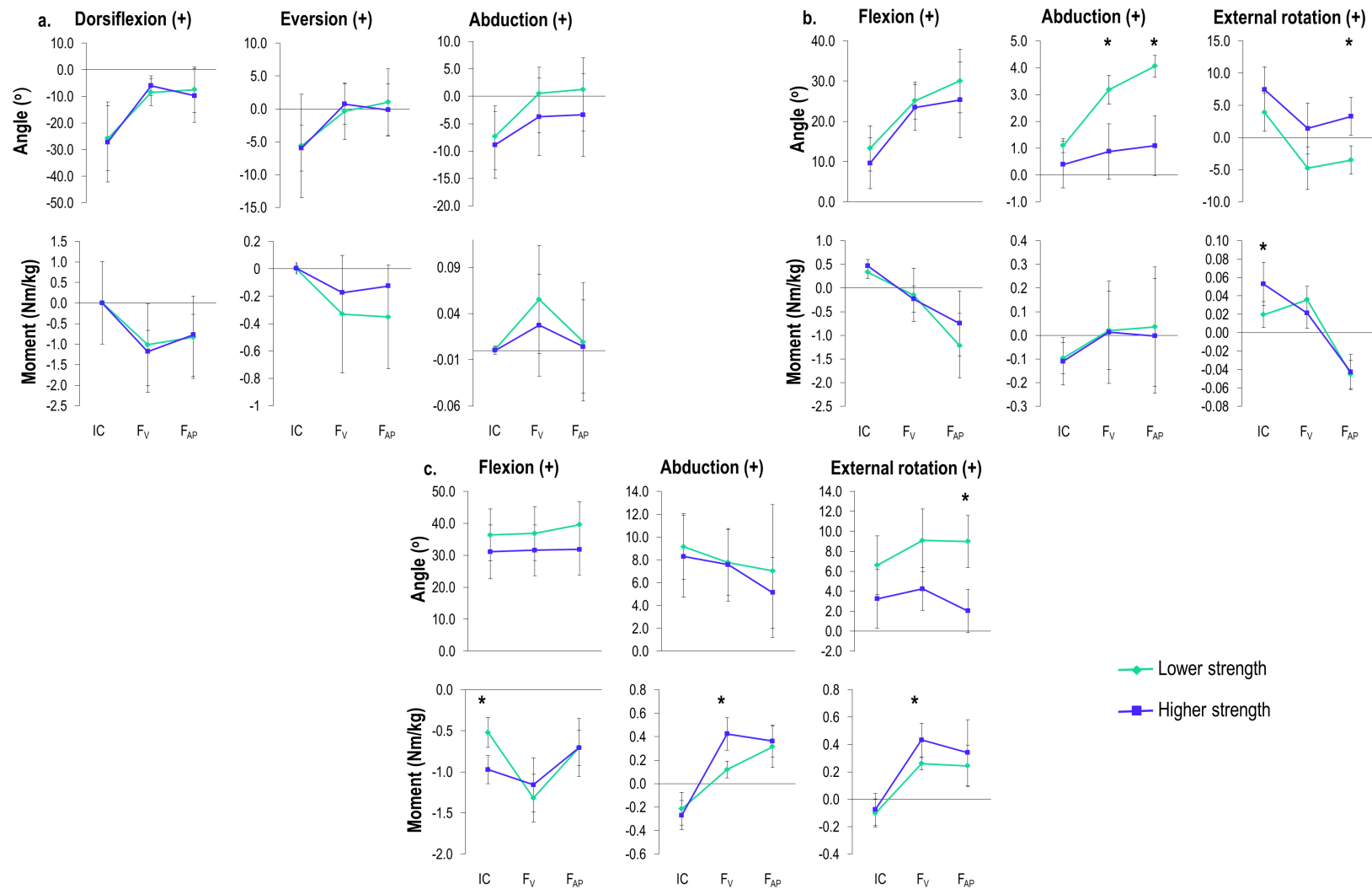


Figure 4.4: Means \pm SD for the three-dimensional (a) ankle (b) knee and (c) hip kinematics and normalised joint moments at the time of initial contact (IC), peak vertical (F_V) and peak anteroposterior (F_{AP}) ground reaction force for the lower and higher hamstring strength groups (* indicates a significant between-group difference at $p \leq 0.05$).

Muscle activation

There were no between-group differences in the timing of muscle onsets or peak activity relative to IC, although high within-group variation was evident (see Table 4.2). Interestingly, although not significant, girls with lower hamstring strength displayed peak ST and MG activity prior to IC, which was not evident in the higher hamstring strength group (see Table 4.2).

Table 4.2: Means \pm SD and p -values for the timing of muscle onsets and peak muscle activity relative to initial contact, for the lower ($n = 11$) and higher ($n = 11$) concentric hamstring strength groups.

Variable	Muscle	Lower strength	Higher strength	p -value
Time of muscle onsets (ms)*	Medial gastrocnemius	-183.4 \pm 78.6	-163.7 \pm 40.5	0.491
	Tibialis anterior	-157.9 \pm 72.7	-169.4 \pm 93.6	0.762
	Vastus medialis	-154.5 \pm 71.3	-143.6 \pm 56.6	0.707
	Rectus femoris	-80.5 \pm 54.4	-99.7 \pm 105.2	0.620
	Biceps femoris	-172.7 \pm 27.4	-165.5 \pm 26.8	0.569
	Semitendinosus	-171.5 \pm 59.5	-201.5 \pm 139.4	0.538
Time of peak activity (ms)	Medial gastrocnemius	-25.0 \pm 47.6	8.5 \pm 51.4	0.148
	Tibialis anterior	113.0 \pm 102.8	131.9 \pm 178.4	0.774
	Vastus medialis	74.1 \pm 55.1	69.8 \pm 13.7	0.810
	Rectus femoris	78.4 \pm 64.9	61.3 \pm 11.8	0.449
	Biceps femoris	60.2 \pm 88.7	79.7 \pm 88.8	0.640
	Semitendinosus	-43.8 \pm 79.8	65.1 \pm 173.7	0.243

* A negative value indicates that the muscle onset or peak activity occurred prior to initial contact.

DISCUSSION

The hamstring muscles play a vital role in protecting the ACL during functional landing movements.⁷ The purpose of this study was to determine whether pubescent girls with lower hamstring strength displayed different lower limb biomechanics when landing after performing a horizontal leap movement, compared to girls with higher hamstring strength. The results of the study confirmed that, as hypothesised, girls with lower hamstring strength modified their landing biomechanics compared to girls with higher hamstring strength, which will be discussed in detail below.

Conventional hamstring-to-quadriceps ($H_{con}:Q_{con}$) ratios are frequently used as an indicator of balance between the flexor and extensor muscles surrounding the knee.^{21, 31} As hypothesised, our results revealed significantly lower $H_{con}:Q_{con}$ ratios in the lower hamstring strength group, relative to their higher strength counterparts. Interestingly, both groups displayed similar absolute and normalised peak quadriceps torque (see Table 4.1) and these values are comparable with those of Ramos et al.³² who reported isokinetic quadriceps torque data collected at 180°/s in pubescent girls. This highlights the fact that the lower strength group were not ‘weaker’ all round, but rather the between-group differences seen in the $H_{con}:Q_{con}$ ratios were specifically due to differences in hamstring strength. A decrease in hamstring strength relative to quadriceps strength is thought to be associated with an increased risk of lower limb injuries, as $H_{con}:Q_{con}$ ratios less than 0.75 at 180°/s have been shown to correlate with greater injury incidence in female athletes.³³ This indicates that girls with lower hamstring strength may be placed at a greater risk of injury, given that their $H_{con}:Q_{con}$ ratio was found to be less than 0.6 (see Figure 4.3). During deceleration from a landing, however, the quadriceps muscles eccentrically rather than concentrically control knee flexion, while, depending on knee and hip alignment, concentric hamstring torque aids to reduce anterior shear forces experienced at the proximal tibia.³¹ Therefore, in order to assess dynamic functionality at the knee in terms of ACL injury risk during a landing, it is important to examine $H_{con}:Q_{ecc}$, as opposed to the more conventional $H_{con}:Q_{con}$ ratios.³¹

In the present study, girls with lower hamstring strength demonstrated almost two-fold lower $H_{con}:Q_{ecc}$ ratios compared to their higher hamstring strength counterparts (see Figure 4.3). Whilst these ratios are well above the previously reported $H_{con}:Q_{con}$ ³³ and $H_{con}:Q_{ecc}$ ³¹ ratios, to our knowledge no research has calculated the $H_{con}:Q_{ecc}$ ratios

corresponding with the knee angle displayed during landing, thus making comparisons to the literature difficult. However, our results suggest that girls with lower hamstring strength may have a reduced capacity for their hamstring muscles to protect the ACL during a dynamic landing movement. Whether girls with lower hamstring strength compensate for this strength deficit via modifying their landing biomechanics compared to girls with higher hamstring strength is discussed below.

Previous research has shown that foot placement during a landing may be implicated in the occurrence of non-contact ACL injuries, such that ACL injured athletes tend to land with less ankle plantar flexion and adopt a more flat-foot alignment, postulated to increase abduction and rotation at the knee.³⁴ Contrary to this belief, both groups in the present study displayed similar ankle kinematics and kinetics (see Figure 4.4a). This highlights the need to determine whether deficits in hamstring strength contribute to between-group differences in knee and hip biomechanics during landing in pubescent girls.

The hamstring muscles can decrease anterior tibial translation and, in turn, loading on the ACL, and thus influence sagittal plane motion at the knee and hip.⁷ Whilst girls with lower hamstring strength displayed lower hip extension moments at the time of IC, we speculate that, based on previously reported moment data,³⁵ a between-group difference of 0.3-0.5 Nm/kg seen in the present study is not functionally relevant. Interestingly, girls with lower hamstring strength experienced significantly greater estimated ACL forces (almost double) at the time of the peak anteroposterior GRF, compared to their higher hamstring strength counterparts. Therefore, given that the participants displayed no differences in sagittal plane biomechanics, it is important to examine the differences in frontal and transverse plane kinetics or kinematics, which

may provide greater insight into the between-group difference in estimated ACL loading.

Increased knee abduction (valgus) angles have been shown to contribute to higher knee abduction loads which, in turn, have been shown to predict ACL injury risk.¹⁵ Girls with lower hamstring strength in the present study displayed greater knee abduction angles at the time of the peak vertical and the peak anteroposterior GRF compared to their higher hamstring strength counterparts. Whilst the 4° between-group difference in knee abduction angle may not seem to be substantial, previous research has shown that a difference as little as 2° in frontal plane alignment reduced the injury threshold (defined as the maximal sustainable GRF before injury occurs) by 1 BW.³⁶ This suggests that girls with lower hamstring strength may be exposed to a greater injury risk due to their greater knee abduction alignment during landing.

Despite greater knee abduction alignment in girls with lower hamstring strength during landing, no differences were evident in frontal plane knee loading (see Figure 4.4b). It is acknowledged that trunk and hip motion can affect biomechanics of the knee and ankle.³⁷ In fact, Jacobs et al.³⁸ reported an association between lower peak isometric hip abductor torque (5.8 and 7.2% of BW x height for women and men, respectively) and increased knee valgus motion (7.3° and 3.3° for women and men, respectively) during a dynamic landing movement in adult females compared to males. Girls with lower hamstring strength in the present study displayed significantly lower hip abduction moments at the time of the peak vertical GRF, despite similar frontal plane hip kinematics. The net internal moments calculated in the present study represent the contribution of the body's soft tissues to oppose the external load on each joint. This decreased hip abduction moment displayed by girls with lower hamstring strength, may suggest a hip abductor weakness and a reduced ability of the hip abductor muscles to

control and reduce frontal plane knee motion during the landing movement,³⁸ potentially contributing to an increased risk of ACL injury. As we did not assess hip abductor muscle activity in the present study, further research is warranted to assess this notion.

Palmieri-Smith et al.³⁹ reported an association between greater knee valgus angles and the lateral thigh musculature activity (vastus lateralis: partial regression coefficient = -1.397, $p = 0.013$; BF: partial regression coefficient = -1.760, $p = 0.008$). Conversely, lower knee valgus angles were associated with heightened medial thigh muscle activation (VM; partial regression coefficient = 2.197, $p = 0.009$). Given the abduction and adduction moment arms of the lateral and medial thigh musculature, respectively,¹² this may explain the increased knee valgus angles typically displayed by females compared to males when landing.^{8, 38} However, despite this association, no between-group differences in the timing of hamstring or quadriceps activation were evident in the present study. Whilst vastus lateralis activity was not collected in the present study, these results suggest that there are no between-group differences in the activation of the lateral (BF) and medial thigh muscles (VM and ST). Therefore, these muscle activation patterns may not be the contributing factor to the greater knee abduction alignment displayed by girls with lower hamstring strength.

Increased knee rotation, particularly internal rotation, has shown to be potentially injurious to the ACL.⁶ Results from the present study revealed a significant difference in the transverse plane knee alignment at the time of the peak anteroposterior GRF, such that participants with lower hamstring strength displayed knee internal rotation and those with higher hamstring strength displayed knee external rotation (see Figure 4.4b). Interestingly, despite a lack of significance (most likely due to the large variation in the data), girls with lower hamstring strength displayed peak ST activity

prior to IC, whereas this peak activity occurred after IC in girls with higher hamstring strength (see Table 4.2). We speculate this earlier ST peak activity may be contributing to greater knee internal rotation in girls with lower hamstring strength,¹¹ potentially contributing to a greater ACL injury risk.⁶ However, due to the large between-subject variation in EMG results, further research involving a significantly larger cohort is recommended to verify this claim.

Whilst a between-group difference in ACL force was detected, this study used a two-dimensional knee model to estimate ACL force. Due to the association between knee abduction, internal rotation alignment and ACL injury risk, further research using a more comprehensive knee model, which incorporates knee frontal and transverse plane motion, is recommended. Additionally, the present study was limited in that it did not assess the strength or activation of the hip abductor muscles or motion of the torso, both of which are known to affect the biomechanics of the lower limbs.³⁷ Furthermore, it is acknowledged that the present study did not examine the intensity of muscle recruitment and results are only based around the temporal aspects of muscle recruitment. Finally, we acknowledge the discrepancy between skin marker movement and actual bone movement is a limitation of the present study. Thus, further research is recommended in these areas to provide a greater understanding of factors affecting lower limb biomechanics during landing.

Overall, it was found that girls who had lower concentric hamstring strength displayed significantly lower hamstring-to-quadriceps ratios, reduced hip abduction moments, greater knee abduction alignment and similar muscle activation patterns during the landing phase of a horizontal landing movement relative to their counterparts with higher hamstring strength. Given that the differences in landing biomechanics displayed by girls with lower compared to higher concentric hamstring strength were

evident from the onset of puberty, as indicated by Tanner Stage II, further research is warranted to determine how landing technique changes throughout the adolescent growth spurt. In summary, girls with reduced hamstring strength appear to have a decreased capacity to control lower limb frontal plane alignment. This reduced capacity appears to contribute to the increased estimated ACL loading and, in turn, increased potential for injury.

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Chapter 5

Does higher anterior knee laxity influence landing biomechanics in pubescent girls?

This chapter is an amended version of the manuscript: Wild CY, Steele JR, Munro BJ. Does higher anterior knee laxity influence landing biomechanics in pubescent girls? *American Journal of Sports Medicine*. To be submitted for publication, August 2012.

ABSTRACT

Background: Increased anterior knee laxity in females is a proposed mechanism for ACL injury, contributing to altered muscle recruitment patterns and higher knee joint loads. Despite a rise in anterior knee laxity during the growth spurt in pubescent girls, it is unknown how lower limb landing mechanics are affected during this time. **Purpose:** To determine whether pubescent girls with higher anterior knee laxity at the time of their PHV displayed different lower limb biomechanics when landing after performing a horizontal leap movement compared to girls with lower anterior knee laxity. **Study Design:** Cross-sectional study. **Methods:** Forty-six girls (10-13 years), confirmed as Tanner Stage II-III, were tested at the time of their PHV. Passive anterior knee laxity was quantified and used to classify participants into higher (HAKL; peak displacement > 4 mm) and lower (LAKL; peak displacement < 3 mm) anterior knee laxity groups (n = 15/group). Participants performed a horizontal leap movement, during which three-dimensional kinematics (100 Hz), GRF and muscle activation patterns (1,000 Hz) were assessed. **Results:** Independent samples *t*-tests indicated there were no significant between-group differences in lower limb isokinetic strength, three dimensional ankle and knee kinematics or peak anteroposterior GRF experienced at landing. However, HAKL girls displayed significantly ($p < 0.05$) reduced hip abduction alignment,

increased hip abduction moments, as well as earlier hamstring muscle and later tibialis anterior activation compared to LAKL girls. **Conclusion:** Earlier hamstring muscle activation may reduce the ability of the muscles to act synergistically with the ACL, increasing the likelihood of injury in girls with higher anterior knee laxity.

INTRODUCTION

With fibre bundles arising from the tibial plateau, anterior and lateral to the medial intercondylar eminence, and extending to the posterior and superior aspect of the medial surface of the lateral femoral condyle,¹ the ACL is a primary passive restraint of the knee, particularly with respect to anterior tibial displacement relative to the femur.² Interestingly, females are exposed to an increased risk of ACL rupture,³ particularly from the onset of puberty.⁴ Increased anterior knee laxity has been proposed as a risk factor for increased ACL injury risk,⁵ thought to reduce the ability of the knee to respond to injurious forces.⁶ Furthermore, throughout puberty, females have been shown to display a 1-2 mm increase in anterior knee laxity^{7, 8} (see Figure 3.5). Uhorchak et al.⁵ reported that an increase in anterior knee laxity of one or more standard deviations above the mean increased the risk of ACL injury as it is thought to contribute to a decrease in knee joint stability.⁹ We postulate that the increase in anterior knee laxity throughout puberty may be a contributing factor to the increased risk of ACL injury incurred by girls at this time in their development.

Non-contact ACL injuries frequently occur in sporting movements that involve rapid deceleration, such as landing from a jump.¹⁰ Women with higher anterior knee laxity have been shown to demonstrate an altered landing strategy, which results in increased knee loads.⁶ Shultz et al.¹¹ reported that women with higher knee laxity (frontal and transverse plane knee laxity) landed with greater hip adduction and internal

rotation, as well as greater knee valgus alignment, compared to women with lower knee laxity. In fact, these lower limb alignments displayed by women with higher knee laxity are also commonly displayed by pubescent girls when they perform drop-landings,^{12, 13} and are thought to place greater strain on the ACL.¹⁴ However, whilst this suggests that greater knee laxity may increase ACL injury risk during landing movements, it is acknowledged that these different measures of knee laxity (frontal and transverse plane, anterior knee laxity, general laxity and genu recurvatum) are not identical in nature.⁶ Furthermore, Park et al.¹⁵ reported that a 1.3 mm increase in anterior knee laxity resulted in a 20% increase in internal knee adduction moments, as well as a 20-45% increase in knee external rotation moments during a dynamic landing task. Whilst these associations are known in adult women, it remains unknown how the increased anterior knee laxity displayed by girls during puberty,^{7, 8} particularly from the time of PHV, influences landing biomechanics and, ultimately, ACL injury risk.

During dynamic landing movements the ACL is assisted in restraining anterior tibial displacement by the hamstring muscles, which apply posterior tibial drawer.¹ This posterior drawer force is generated in an attempt to counteract the anterior force applied to the tibia by the quadriceps muscles, which work eccentrically to control knee flexion upon initial contact with the ground.¹⁶ Females, however, display a lag in development of their hamstring muscle strength relative to their quadriceps muscle strength during puberty,¹⁷ which may in turn decrease the ability of their hamstring muscles to protect the ACL during dynamic movements.¹ Rozzi et al.¹⁸ reported that females displayed greater anterior knee laxity compared to their male counterparts, as well as greater lateral hamstring activation ($p = 0.002$) when performing a drop landing. This altered muscle activation was suggested to be a strategy adopted by females to compensate for their increased joint laxity and decreased knee joint

stability.¹⁸ However, whilst females with greater anterior knee laxity display an increased time to detect knee joint motion,¹⁸ it is unknown whether pubescent girls display increased hamstring muscle strength or altered muscle recruitment patterns in order to compensate for their increased anterior knee laxity during their adolescent growth spurt.

Compared to boys, girls experience a significant increase in anterior knee laxity from the time of PHV and throughout puberty,⁷ as well as a lag in the development of hamstring muscle strength¹⁷ (see Chapter 3), potentially decreasing the ability of their hamstrings to assist the ACL. However, whilst the influence of higher anterior knee laxity during drop-landings in adult women has been demonstrated,^{6, 15, 18} this has yet to be shown in pubescent girls, particularly during the performance of a sport-specific, horizontal landing movement. Furthermore, as the lower limb acts as a closed kinetic chain during a landing movement, movement of the ankle and hip has the ability to affect knee biomechanics, and vice versa. Therefore, the purpose of this study was to determine whether pubescent girls with higher anterior knee laxity at the time of their PHV displayed differences in lower limb strength as well as lower limb biomechanics when landing after performing a horizontal leap movement compared to girls with lower anterior knee laxity. Based on the literature, it was hypothesised that, compared to girls with lower anterior knee laxity, girls with higher anterior knee laxity would display significantly greater isokinetic strength, altered lower limb kinematics, higher kinetics, as well as significantly earlier lower limb muscle onsets relative to IC, in an attempt to stabilise their knee while landing.

METHODS

Participants

Seventy-one healthy, female volunteers aged between 10-13 years were initially screened for their Tanner stage of pubertal development,¹⁹ as well as their estimated maturity offset (coinciding with the time of PHV).²⁰ Each girl's Tanner stage was self-assessed using modified Tanner stage diagrams¹⁹ (see Appendix A) and maturity offset was estimated using a sex-specific multiple regression equation²⁰ (see Appendix B). Forty-six girls satisfied the inclusion criteria (Tanner Stage II-III of pubic hair development and 0 months from PHV) and were recruited as participants. Girls were excluded if they did not satisfy the developmental inclusion criteria, had a lower limb injury that prevented them from participating in physical activity or sport, or had begun menstruating. The University of Wollongong Human Research Ethics Committee (HE08/281) approved all study procedures and the participants and their parents/guardians provided informed written and verbal consent prior to the girls participating in the study.

Anterior knee joint laxity

Passive anterior knee laxity was characterised by measuring the anterior tibial displacement for each participant's dominant limb using a Dynamic Cruciate Tester (DCT; Smith & Nephews Richards, Australia) and following methods that have been previously reported (see Chapter 3; Figure 3.3). Following 1-2 familiarisation trials, three passive anterior drawer tests were performed. Anterior tibial translation (mm) and the force applied by the participant's leg against the strain-gauged ankle strap (N) were simultaneously recorded as force-displacement curves. The peak anterior displacement, averaged over three trials, was recorded to represent each participant's anterior knee

laxity. The chief investigator [CYW] performed all anterior knee laxity measurements, after confirming she was reliable ($ICC > 0.9$) in taking these measurements.

Isokinetic lower limb strength

After completing a standardised 5-10 minute warm-up on a cycle ergometer (Monark Model 818E, Sweden), each participant's hamstring and quadriceps muscle strength was assessed using an isokinetic dynamometer (KinCom, Chattanooga Inc., USA), following standardised procedures²² (see Chapter 3 for isokinetic strength testing methodology). Overall, participants performed one test for each of the strength measures (concentric hamstrings, eccentric hamstrings, concentric quadriceps and eccentric quadriceps) in a randomised order and the peak torque was recorded. Participants were allowed adequate rest between each trial to reduce the effects of fatigue on peak torque values.

Landing task

The participants were required to perform a horizontal, single-limb, landing movement (see Figure 4.1). A horizontal landing task was selected due to the fact that this type of movement is more specific to the implications for ACL injury, rather than the previously utilised box-drop landing.^{12, 13, 17, 23} In order to ensure consistency across all trials each participant was adequately familiarised with the landing task.

Data collection and analysis during landing

During the landing movement, the three orthogonal components of the GRF generated by each participant upon landing were measured (1,000 Hz), using a calibrated multichannel force platform (Type 9281B; Kistler, Switzerland; 600 mm x

400 mm) embedded in the laboratory floor, and amplified using a Kistler Multichannel charge amplifier (Type 9865A; Kistler, Switzerland). The raw GRF data were filtered using a fourth-order zero-phase-shift Butterworth digital low-pass filter ($f_c = 100$ Hz) before calculating the magnitude and timing of the peak anteroposterior GRF component (normalised to each participant's BW; positive values indicated an anterior GRF). The force data were also used to determine the time of IC of the foot with the force platform upon landing.

The three-dimensional motion (100 Hz) of each participant's test limb during the landing task was recorded using an OptoTRAK 3020 motion analysis system (Northern Digital Inc, Canada). Eighteen infrared-emitting diodes were adhered to anatomical landmarks on each participant's test limb (see Chapter 4). A three-dimensional model of the foot, shank, thigh and pelvis segments of each participant's test limb was then created in Visual3D (Version 4, C-Motion Inc, USA) from a standing calibration file of each participant and based on each participant's inertial properties.²⁴ The three-dimensional ankle, knee and hip joint angles (whereby positive angles were defined as dorsiflexion, eversion and forefoot abduction for the ankle; and flexion, abduction and external rotation for the knee and hip), were then calculated at the time of the peak anteroposterior GRF.

The raw kinematic, GRF, free moment and centre of pressure data were then filtered using a fourth-order zero-phase-shift Butterworth digital low-pass filter ($f_c = 14$ Hz; determined using residual analysis),²⁵ prior to calculating the lower limb kinematics and joint moments.²⁶ The filtered three-dimensional ankle, knee and hip internal joint moments (Nm) at the time of the peak anteroposterior GRF were then calculated using an inverse dynamics approach.²⁵ Positive moments were defined as

dorsiflexion, eversion and forefoot abduction for the ankle; extension, abduction and external rotation for the knee; and flexion, abduction and external rotation for the hip.

Activity of medial gastrocnemius (MG), tibialis anterior (TA), vastus medialis (VM), rectus femoris (RF), semitendinosus (ST) and biceps femoris (BF) of each participant's test limb were recorded using bipolar Ag-AgCl surface electrodes (2 cm inter-electrode spacing; Blue Sensor Type M-OO-S, Medico test, Denmark) following standard preparation.²⁷ The filtered EMG signals were visually inspected, using a threshold detector of 8% of the maximum amplitude of the muscle burst of interest²⁸ in order to determine the timing of muscle onsets and peak muscle activity relative to IC (whereby a negative value indicated that the timing of the muscle onset or the peak muscle activity occurred prior to IC). The kinematic, GRF and EMG data were time synchronised and collected using First Principles software (Version 1.2.2; Northern Digital, Canada).

Statistical analyses

In order to assess whether anterior knee laxity affected landing biomechanics, the 46 participants were divided into a higher anterior knee laxity group (HAKL; peak anterior tibial displacement > 4 mm; n = 15) and lower anterior knee laxity (LAKL; peak anterior tibial displacement < 3 mm; n = 15) group. The 16 participants (the middle third based on tertile categorisation) whose peak anterior tibial displacement was measured to be between 3-4 mm were removed from further analysis to ensure a significant between-group difference in anterior knee laxity ($p < 0.001$; see Table 5.1 for participant characteristics). Jump distance during the experimental landing task was similar between the two groups ($p = 0.930$; 1.22 ± 0.17 m and 1.21 ± 0.36 m, for the HAKL and LAKL groups, respectively). The sample size provided sufficient statistical

power ($> 80\%$) to detect significant main effects at $p \leq 0.05$ (when anterior knee laxity was used as the outcome measure) between the higher and lower anterior knee laxity groups.²⁹

Means and standard deviations for the anterior knee laxity, hamstring and quadriceps isokinetic strength, lower limb kinematics and moments, GRF and EMG variables were calculated for the higher and lower anterior knee laxity groups. Independent samples *t*-tests were then applied to the data to determine whether there were any significant ($p \leq 0.05$) differences in the lower limb strength and landing biomechanics displayed by the HAKL group relative to their LAKL counterparts during the horizontal leap task. Although multiple comparisons were made, no adjustment to the alpha level was deemed necessary given the exploratory nature of the present study and because such adjustments may increase the likelihood of Type II errors.³⁰ All statistical procedures were conducted using SPSS (Version 17; SPSS Inc., Chicago, IL).

Table 5.1: Participant characteristics and lower limb strength for the higher (HAKL; $n = 15$) and lower (LAKL; $n = 15$) anterior knee laxity groups (means \pm SD; * indicates a significant between-group difference at $p \leq 0.05$).

Variable	HAKL	LAKL	<i>p</i> -value
Height (cm)	154.6 \pm 6.0	152.4 \pm 4.1	0.239
Lower limb length (cm)	73.9 \pm 4.3	71.9 \pm 2.9	0.133
Torso length (cm)	80.6 \pm 2.6	80.5 \pm 2.5	0.834
Mass (kg)	44.0 \pm 5.3	41.2 \pm 4.2	0.107
Height velocity (cm/yr)	12.3 \pm 3.4	9.5 \pm 2.4	0.010*
Tanner Stage	II	II	0.532
Concentric hamstring torque (Nm)	31.5 \pm 7.6	33.5 \pm 10.6	0.545
Eccentric hamstring torque (Nm)	53.1 \pm 15.0	55.0 \pm 14.0	0.708
Concentric quadriceps torque (Nm)	47.0 \pm 19.2	43.7 \pm 9.2	0.541
Eccentric quadriceps torque (Nm)	84.7 \pm 32.3	88.0 \pm 19.7	0.730
Anterior knee laxity (mm)	5.2 \pm 0.8	2.4 \pm 0.5	<0.001*

RESULTS

Despite both groups being recruited at the time of PHV, results showed that girls with higher anterior knee laxity displayed significantly greater height velocity compared

to girls with lower anterior knee laxity (see Table 5.1). However, there were no differences in any of the other anthropometric or lower limb strength results between the two groups.

Overall, the groups displayed similar ($p > 0.05$) three-dimensional ankle and knee kinematics at the time of the peak anteroposterior GRF (see Table 5.2). However, HAKL girls displayed significantly less hip abduction compared to their LAKL counterparts (see Table 5.2). Girls with higher anterior knee laxity also displayed significantly greater ankle plantar flexion ($p = 0.002$) and hip abduction ($p = 0.005$) moments, compared to girls with lower anterior knee laxity, but no differences in knee moments at the time of the peak anteroposterior GRF were evident (see Table 5.2).

Table 5.2: Means \pm SD and p -values for the three-dimensional ankle, knee and hip joint angles and internal joint moments at the time of the peak anteroposterior ground reaction force for the higher (HAKL; $n = 15$) and lower (LAKL; $n = 15$) anterior knee laxity groups (* indicates a significant between-group difference at $p \leq 0.05$).

Variable	HAKL	LAKL	p -value
Joint angle ($^{\circ}$)^a			
Ankle dorsiflexion	-7.2 ± 9.7	-9.7 ± 5.3	0.403
Ankle eversion	0.5 ± 4.3	-1.4 ± 3.6	0.197
Ankle abduction	-2.2 ± 6.7	-2.8 ± 3.1	0.785
Knee flexion	29.7 ± 10.9	25.8 ± 5.2	0.228
Knee abduction	2.1 ± 3.4	2.2 ± 4.9	0.935
Knee external rotation	0.2 ± 5.7	1.7 ± 4.9	0.437
Hip flexion	37.9 ± 10.7	44.3 ± 9.7	0.098
Hip abduction	4.8 ± 2.8	9.7 ± 1.2	0.024*
Hip external rotation	4.8 ± 6.9	4.3 ± 5.9	0.846
Joint moment (Nm)^b			
Ankle dorsiflexion	-35.7 ± 11.5	-13.7 ± 13.3	0.002*
Ankle eversion	-8.6 ± 9.4	-4.6 ± 5.1	0.171
Ankle abduction	0.3 ± 2.2	0.1 ± 1.8	0.719
Knee extension	35.4 ± 28.5	29.1 ± 21.7	0.503
Knee abduction	5.0 ± 7.6	2.3 ± 9.3	0.386
Knee external rotation	-4.1 ± 4.9	-1.1 ± 3.1	0.069
Hip flexion	-37.3 ± 16.4	-41.2 ± 16.9	0.533
Hip abduction	19.5 ± 10.3	4.7 ± 8.4	0.005*
Hip external rotation	18.2 ± 12.4	11.6 ± 9.1	0.114

a. Positive joint angles defined as dorsiflexion, eversion and forefoot abduction for the ankle; and flexion, abduction and external rotation for the knee and hip.

b. Positive internal joint moments defined as dorsiflexion, eversion and forefoot abduction for the ankle; extension, abduction and external rotation for the knee; and flexion, abduction and external rotation for the hip.

The timing of muscle onsets relative to the timing of IC for the two participant groups are displayed in Figure 5.1. Overall, despite high within-group variation, results showed a significant between-group difference for the timing of TA onset ($p = 0.04$), such that the HAKL girls activated TA significantly later compared to the LAKL participants. Significant between-group differences in the timing of ST ($p = 0.016$) and BF ($p = 0.004$) were also displayed, such that the HAKL group activated their hamstring muscles significantly earlier compared to the LAKL group (see Figure 5.1). No between-group differences in timing of the peak muscle activation relative to IC were evident (see Table 5.3).

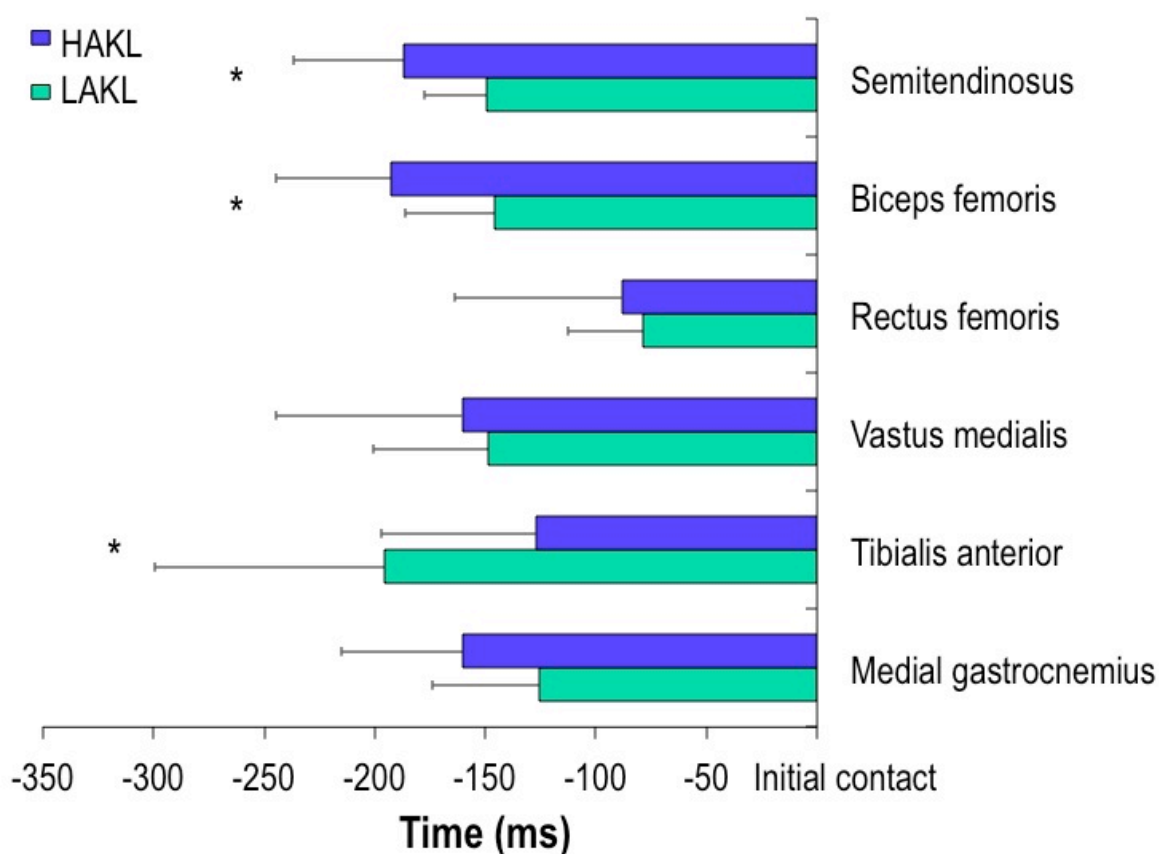


Figure 5.1: Means \pm SD for the timing of muscle onsets relative to initial contact (ms) for the higher (HAKL; $n = 15$) and lower (LAKL; $n = 15$) anterior knee laxity groups (a negative value indicates the muscle onset occurred prior to initial contact; * indicates a significant between-group difference at $p \leq 0.05$).

No between-group differences were found for the peak anteroposterior GRF ($p = 0.233$), whereby values of -0.92 ± 0.21 BW and -1.15 ± 0.31 BW were calculated for the higher and lower anterior knee laxity groups, respectively. Furthermore, no differences ($p = 0.066$) in the timing of peak anteroposterior GRF were displayed between the HAKL (30.3 ± 6.4 ms) and the LAKL (25.7 ± 9.6 ms) groups.

Table 5.3: Means \pm SD and p -values for the timing of the peak muscle activity relative to initial contact (ms) for the higher (HAKL; $n = 15$) and lower (LAKL; $n = 15$) anterior knee laxity groups.

Muscle Variable (ms)	HAKL	LAKL	p -value
Medial gastrocnemius ^a	31.6 ± 53.3	30.8 ± 53.9	0.969
Tibialis anterior	80.4 ± 80.3	116.8 ± 99.7	0.271
Vastus medialis	70.0 ± 38.3	61.6 ± 21.2	0.485
Rectus femoris	75.0 ± 50.5	76.0 ± 32.3	0.950
Biceps femoris	37.4 ± 58.9	51.2 ± 89.3	0.604
Semitendinosus	89.8 ± 36.7	76.9 ± 48.5	0.256

a. A positive value indicates that the peak muscle activity occurred after initial contact.

DISCUSSION

An increase in anterior knee laxity has been suggested to decrease knee joint stability,⁹ and ultimately increase the likelihood of an ACL rupture.⁵ The purpose of this study was to determine whether pubescent girls with higher anterior knee laxity at the time of their PHV displayed different lower limb biomechanics when landing after performing a horizontal leap movement compared to girls with lower anterior knee laxity. As hypothesised, girls with higher anterior knee laxity displayed compensatory landing biomechanics compared to their counterparts with lower anterior knee laxity. It is important to note that whilst the present study utilised the DCT for anterior knee laxity measurements, the overall group mean (approximately 4 mm) is similar to those previously reported for females between Tanner Stages II-III using other arthrometers such as the KT-2000.⁸

The rapid growth in height displayed by girls at the time of PHV coincides with a time during puberty when girls have displayed increases in knee laxity^{7, 8} (see Figure 3.5), potentially demonstrating a ‘high risk’ time during the growth spurt in terms of ACL injury risk. Despite the fact that all participants in the present study were at the same stage of their growth spurt (PHV), girls with higher anterior knee laxity were growing significantly faster (12.3 cm/yr) compared to girls with lower anterior knee laxity (9.5 cm/yr). Although an unexpected finding, it is unknown whether this increased height velocity in the HAKL group contributed to their greater ligament laxity.

During the adolescent growth spurt, bones grow faster than the developing musculature and the peak growth velocity of the more distal segments, such as the foot, occurs before that of the more proximal segments, such as the shank and the thigh.³¹ This growth differential alters the moment of inertia of the lower limb segments, inevitably requiring a change in muscular torque in order to accelerate and decelerate the limbs during dynamic landing tasks.^{32, 33} We postulate that girls with higher anterior knee laxity may be more reliant on the active structures of the knee, including the hamstring and quadriceps muscles, to provide stability to the knee joint during this time of rapid growth.

During a landing movement, eccentric quadriceps contraction acts to prevent the knee from collapsing into flexion, whilst the hamstring muscles aid in protecting the ACL by imparting a posterior drawer to the tibia.¹⁶ The thigh muscles are therefore integral to active stability of the knee joint during landing.³⁴ In the present study, girls with higher anterior knee laxity displayed similar lower limb isokinetic strength compared to girls with lower anterior knee laxity. Therefore, given the rapid changes in lower limb proportionality in girls with higher anterior knee laxity and, in turn

potentially reduced knee joint stability,^{9, 18} we believe that greater strength, particularly of the hamstring muscles, is required to protect the ACL during landing in this participant group. For these reasons, we believe that girls with higher anterior knee laxity, who did not display an increase in hamstring muscle strength relative to their counterparts with less anterior knee laxity, may be at a greater risk of sustaining an ACL rupture when performing dynamic landing tasks.

Similar to Shultz et al.,¹¹ and despite between-study differences in knee laxity measures, girls with higher knee laxity in the present study displayed less hip abduction alignment during landing. Increased hip adduction (or reduced hip abduction as displayed in the present study), in combination with an increased knee abduction alignment during landing, is a dynamic posture associated with increased ACL injury risk.¹¹ Interestingly, girls with higher anterior knee laxity displayed significantly greater internal hip abduction moments during landing, potentially in an effort to control hip motion.³⁵ However, given that no between-group differences in knee kinematics were evident, the question is raised as to whether this increased hip abductor moment and altered hip alignment in girls with higher anterior knee laxity is favourable or not to the ACL during landing, highlighting the need for further research in this area.

Despite no between-group differences in hamstring muscle strength, girls with higher anterior knee laxity displayed significantly earlier hamstring muscle activation compared to girls with lower anterior knee laxity. Rozzi et al.¹⁸ reported a significant relationship ($p = 0.002$) between increased anterior knee laxity and greater peak lateral hamstring (BF) activity in adult females compared to males. This increased muscle intensity was suggested to be a compensatory mechanism developed by women over time in an attempt to stabilise and protect their lower limb and ACL during landing.¹⁸ However, Rozzi et al.¹⁸ did not report any between-group differences in timing of the

hamstring muscle onsets relative to IC. Interestingly, Cowling et al.¹⁶ reported that adult males activated their medial hamstring muscles significantly later compared to females (91-98 ms and 115-125 ms prior to IC, respectively), during a horizontal leap landing movement. This delayed hamstring muscle activation has also been displayed in ACL deficient athletes compared to their matched uninjured controls.²⁸ These authors suggested that the delay in hamstring muscle activation was a strategy to allow the peak hamstring activity to better coincide with the peak tibiofemoral shear forces, thereby acting synergistically with the ACL.^{16, 28} In the present study no analysis of muscle intensity data was completed and there were no differences in the timing of the peak activity of the hamstring muscles (see Table 5.3). Therefore, while the earlier hamstring activation in HAKL girls may demonstrate a compensatory mechanism in an attempt to stabilise their more lax knees, we suggest that this altered muscle recruitment pattern may reduce the ability of the hamstring muscles to act synergistically with the ACL, thereby increasing their risk of injury during the performance of horizontal leap landing movements.^{16, 28}

In addition to earlier hamstring muscle activation, girls with higher anterior knee laxity also displayed later TA activation compared to their lower laxity counterparts. Elias et al.² showed that contracting the soleus muscle caused posterior tibial translation, demonstrating the ability of soleus to act synergistically with the ACL.¹ Given the muscle's attachment,¹ TA has the potential to facilitate anterior tibial translation, thereby acting agonistically with the quadriceps to work against the ACL.² Although speculative, the later TA activation displayed by HAKL girls in the present study may also be a compensatory mechanism developed by these girls in an attempt to minimise the potential for anterior tibial translation, as well as the reduced ability of the hamstring muscles to act synergistically with, and protect the ACL. However, further

research is recommended to determine the role of this delayed TA activation in ACL injury mechanisms, as well as the longitudinal changes to TA activation throughout the growth spurt, particularly with respect to the rapid increase in anterior knee laxity displayed at the time of PHV (see Chapter 3).

The authors acknowledge that the present study did not examine the intensity of muscle recruitment and results are only based around the timing of muscle onsets and peak activity relative to IC. Therefore, further research is warranted in order to ascertain whether earlier hamstring muscle activation is accompanied by an increase in muscle intensity, lower limb muscle fatigue and, ultimately, ACL injury risk. Whilst girls in the present study were divided into higher and lower anterior knee laxity groups, it is unknown whether HAKL girls are inherently more lax, or whether this increased ligament laxity is due to their more rapid growth compared to LAKL girls (see Table 5.1). Finally, the nature of the present study was cross-sectional in design, thus participants were only tested during one stage of their adolescent growth spurt (PHV). Therefore, it is unknown whether girls display similar neuromuscular recruitment patterns with the rapid increases in anterior knee laxity displayed throughout their growth spurt (see Chapter 3). Therefore, further research is now recommended to determine longitudinally how landing technique, including neuromuscular recruitment, changes throughout the adolescent growth spurt in girls, particularly with respect to changes in anterior knee laxity.

CONCLUSION

Compared to girls with lower anterior knee laxity, girls with higher anterior knee laxity displayed significantly greater height velocity with no concurrent increase in hamstring or quadriceps muscle strength to assist in controlling their more rapidly

growing lower limb segments or potentially less stable knee joint structures.^{9, 18, 31, 32}

The girls with higher anterior knee laxity also displayed similar ankle and knee kinematics and kinetics but reduced hip abduction alignment, increased hip abduction moments, as well as significantly earlier hamstring and later TA activation prior to landing, relative to girls with lower anterior knee laxity. This earlier hamstring muscle activation may reduce the ability of the muscles to act synergistically with the ACL and, in turn, increase the likelihood of ACL injury. Further research is warranted, however, to confirm the role of these neuromuscular recruitment patterns in ACL injury.

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Chapter 6

How does lower limb landing technique develop throughout the adolescent growth spurt in girls?

This chapter is an amended version of the manuscript: Wild CY, Steele JR, Munro BJ. Development of landing biomechanics throughout the adolescent growth spurt in girls. *Medicine & Science in Sports & Exercise*. To be submitted for publication, August 2012.

ABSTRACT

Despite the rapid musculoskeletal changes experienced by girls throughout the adolescent growth spurt, little is known about how lower limb landing technique changes throughout this time. **Purpose:** To investigate the longitudinal changes in the three-dimensional lower limb kinematics, joint moments and muscle activation patterns displayed by girls during the performance of a horizontal landing task throughout their adolescent growth spurt. **Methods:** Thirty-three healthy, 10-13 year-old girls, in Tanner Stage II, with a maturity offset of -6 to -4 months (time from PHV), were initially recruited. According to their maturity offset, each participant was tested up to four times during the 12 months of their growth spurt (Test 1: maturity offset = -6 to -4 months, Test 2: maturity offset = 0 months, Test 3: maturity offset = +4 months, Test 4: maturity offset = +8 months). During each test session, participants performed a horizontal leap movement, during which GRF (1,000 Hz), lower limb EMG (1,000 Hz) and kinematic data (100 Hz) were collected. **Results:** Throughout the growth spurt, girls displayed a decrease in knee flexion alignment ($p = 0.028$), an increase in hip flexion alignment ($p < 0.047$), higher knee ($p < 0.009$) and hip ($p < 0.024$) adductor moments, as well as less muscle co-contraction upon landing. **Conclusions:** During their adolescent growth

spurt, pubescent girls display a change in the strategy with which they control their lower limb to land after performing a horizontal leap movement. These changes are likely to be in response to the longitudinal musculoskeletal changes occurring during this period of rapid growth.

INTRODUCTION

During the adolescent growth spurt girls experience a vast number of rapid and sizeable changes to their musculoskeletal structure and function, including increases in height and lower limb length, increases in passive anterior knee laxity, as well as a lag in the development of their hamstring relative to their quadriceps muscle strength (see Chapter 3). These musculoskeletal changes, specifically the lag in the development of their hamstring relative to their quadriceps muscle strength throughout puberty (see Chapter 3), have the potential to place girls at an increased risk of incurring a non-contact ACL rupture, an injury that is prevalent in girls following the onset of puberty.¹ Whilst some of these musculoskeletal changes have been shown to affect landing technique in cross-sectional studies (see Chapter 4 and 5), the longitudinal effect of these changes on the landing biomechanics displayed by pubescent girls, remains unclear.

In a cross-sectional study on 100 females and 80 males, Hewett et al.² reported that from early (Tanner Stage II-III) to late (Tanner Stage IV-V) puberty, girls displayed a 10° increase in peak knee abduction angle during a box-drop landing task, although this increase was not displayed by their male counterparts. These results were confirmed in a recent longitudinal study on 145 pubertal females and 37 pubertal males.³ That is, although not specifying Tanner Stage, Ford et al.³ found that from the first to the second year of their growth spurt (defined using regression equations to predict adult stature),

girls displayed a significant increase of 2° in peak knee abduction angle when performing a box-drop landing, whereas boys showed no substantial change in this variable (mean change = 0.1°) over time.³ Ford et al.³ also reported a significant increase in knee abduction moments for both boys and girls (approximate increase of 3-5 Nm) throughout puberty. Increased knee abduction alignment during landing has been shown to contribute to high internal knee adduction loads (moments), which in turn, can predict ACL injury status ($r^2 = 0.88$).⁴ However, although the study by Ford et al.³ was longitudinal in design, participants were only tested once a year over two years, which may not be frequent enough to report changes in lower limb landing biomechanics that occur throughout the adolescent growth spurt. Furthermore, the above studies only investigated the biomechanics of one joint (knee), in one plane of motion (coronal). During landing, the three-dimensional motion and moments about the ankle and hip joints can affect knee biomechanics and, in fact, have been implicated in ACL injuries incurred by females.^{5, 6} Therefore, studies investigating the landing technique displayed by pubescent girls longitudinally throughout the adolescent growth spurt, should examine the kinematics and joint moments of the entire lower limb, rather than just focus on the knee joint.

When investigated longitudinally throughout their growth spurt, girls have been shown to display a lag in the development of their hamstring relative to their quadriceps muscle strength (see Chapter 3). The cross-sectional effect of this lag in hamstring strength development has been associated with an increase knee abduction alignment, and ultimately ACL load, during the performance of a horizontal landing movement (see Chapter 4). However, the effect of these strength changes on the neuromuscular control of these muscles throughout puberty during the performance of dynamic landing activities, has not been documented. Inefficient neuromuscular recruitment can

influence how an individual positions their lower limb during a landing,⁷ as well as the ability of these muscles to protect the lower limb, and particularly the ACL, during a landing.⁸ In fact, adult males have been shown to display a delay in the activation of their hamstring muscles prior to landing from a horizontal movement, compared to their female counterparts.⁸ The authors suggested this delayed activation represented a more effective hamstring muscle recruitment strategy,⁸ allowing their hamstring muscles to better act as ACL synergists and, in turn, decrease the potential for ACL injury.^{8, 9} Lazaridis et al.¹⁰ reported that pre-pubescent boys aged between 9-11 years displayed greater co-contraction of their tibialis anterior, soleus and medial gastrocnemius muscles [calculated as the intensity of: tibialis anterior/(medial gastrocnemius + soleus)] when landing from a box-drop jump, compared to their adult male counterparts who were aged between 19-27 years (0.82 and 0.46, respectively). We suggest that this co-contraction muscle recruitment strategy may provide the boys with increased ankle joint stability, particularly during the performance of such a dynamic task.^{10, 11} However, there is a distinct lack of longitudinal research investigating the neuromuscular activation patterns displayed by pubescent girls when they perform a horizontal landing task, throughout the span of their growth spurt.

Whilst girls display an increased risk of ACL injuries from the onset of puberty¹ and landing mechanisms account for 12% of these injuries,¹² there is a paucity of research pertaining to the longitudinal changes in the three-dimensional ankle, knee and hip landing biomechanics displayed by girls during their adolescent growth spurt. Therefore, the purpose of this study was to investigate the longitudinal changes in the three-dimensional lower limb kinematics, joint moments and muscle activation patterns displayed by girls during the performance of a horizontal landing task throughout their adolescent growth spurt. Due to the rapid growth and musculoskeletal changes

experienced throughout puberty (see Chapter 3), it was hypothesised that girls would display significant changes in their three-dimensional lower limb ROM and alignment, specifically an increase in knee abduction; increased joint loading, specifically an increase in coronal plane knee moments; as well as changes in their lower limb neuromuscular recruitment, specifically a decrease in muscle co-contraction, throughout the adolescent growth spurt.

METHODS

Participants

Initially, 71 healthy, female volunteers aged 10-13 years were screened for their Tanner stage of pubertal development¹³ and their estimated maturity offset, to determine pubertal onset.¹⁴ Due to ethical constraints and in an attempt to reduce participant burden, each girl's Tanner stage was self-assessed, with the assistance of a parent and/or guardian, using simplified Tanner stage line drawings of pubic hair development (see Appendix A).¹⁵ Maturity offset was estimated using a sex-specific multiple regression equation based on each participant's body mass, standing and sitting height, lower limb length and chronological age, which can estimate maturity offset within ± 1 year 95% of the time¹⁶ (see Appendix B).

Thirty-three girls satisfied the initial inclusion criteria for the first test session (healthy female, aged 10-13 years, Tanner Stage II of pubic hair development, maturity offset = -6 to -4 months) and were recruited as participants. Girls were excluded if they did not satisfy the developmental inclusion criteria, had a lower limb injury that prevented them from completing the experimental task, or had begun menstruating. A complete outline of the study design is depicted in Figure 3.1. In brief, the remaining 38 volunteers who did not satisfy the initial inclusion criteria for testing were re-screened

approximately 6 months later, whereby 13 of these girls satisfied the inclusion criteria and were therefore recruited for the second test session (Test 2; Tanner Stage II-III and maturity offset = 0 months) and the remaining 25 girls were excluded from the study (see Figure 3.1). Due to cyclic fluctuations in hormones and knee laxity,¹⁷ participants who reached menarche at any point during the 12-month testing period were excluded from the study at this point and, due to participant availability, 15 participants did not complete the final test session (Test 4; see Figure 3.1). Based on the method of Bach and Sharpe,¹⁸ the sample size was shown to provide sufficient statistical power ($> 80\%$) to detect significant main effects at $p \leq 0.05$ when comparing the longitudinal changes in the dependent variables over time, when standing height was used as the outcome measure (standard deviation of the differences in measurements = 0.75 cm). All participants were recruited through local (Illawarra region) newspapers in order to ensure the participants represented a general, pubescent female cohort, with minimal sample bias. The University of Wollongong Human Research Ethics Committee (HE08/281) approved all study procedures and the participants and their parents/guardians provided informed written and verbal consent before the girls participated in the study.

Study design and experimental protocol

During the 12-month period of their adolescent growth spurt, each participant was tested in the Biomechanics Research Laboratory up to four times. The timing of each testing session was based around maturity offset (Test 1: maturity offset = -6 to -4 months, Test 2: maturity offset = 0 months, Test 3: maturity offset = +4 months, Test 4: maturity offset = +8 months). Maturity offset was estimated using a sex-specific regression equation,¹⁶ using previously described methods (see Chapter 3 and

Appendix A). Participant characteristics, including standing height, lower limb length, sitting height (torso) length, body mass, chronological age and Tanner stage, for each testing session, as well as the methods used to calculate these variables have been previously reported for this cohort (see Chapter 3). Each testing session was identical in nature, whereby each participant's three-dimensional lower limb landing biomechanics were measured within the laboratory setting. The chief investigator [CYW] conducted each testing session and performed all measurements at approximately the same time of day for each individual participant.

Landing task

Following preparation, each participant was adequately familiarised with the landing task, so as to ensure consistency across trials. The landing task (depicted in Figure 4.1), was chosen as it is horizontal in nature and thus more task specific when developing implications for ACL injury compared to tasks such as box-drop landings.^{2, 19, 20} Despite the fact that all participants performed the landing task with maximal effort during each test session, there was no significant ($p = 0.953$) effect of time on the horizontal jump distance over the 12 months (Test 1 = 1.21 ± 0.03 m, Test 2 = 1.22 ± 0.03 m, Test 3 = 1.21 ± 0.03 m and Test 4 = 1.23 ± 0.04 m).

Data collection and analysis

The three orthogonal components of each GRF vector generated by participants upon landing were measured (1,000 Hz) using a calibrated multichannel force platform (Type 9281B; Kistler, Switzerland; 600 mm x 400 mm) embedded in the laboratory floor and amplified using a Kistler Multichannel charge amplifier (Type 9865A; Kistler, Switzerland). The raw GRF data were filtered using a fourth-order zero-phase-shift

Butterworth digital low-pass filter ($f_c = 100$ Hz) before calculating the time each participant contacted the ground (IC), as well as the time of the peak anteroposterior GRF (F_{AP}).

The three-dimensional motion (100 Hz) of each participant's test limb during the landing task was recorded using an Opto**TRAK** 3020 motion analysis system (Northern Digital Inc, Canada). Eighteen infrared-emitting diodes were adhered to 18 anatomical landmarks (see Chapter 4) on each participant's test limb. A three-dimensional model of the foot, shank, thigh and pelvis segments of the test limb was then created in Visual3D (Version 4, C-Motion Inc, USA) from a standing calibration file of each participant and based on each participant's inertial properties.²¹ The three-dimensional ankle, knee and hip joint angles (whereby positive angles were defined as dorsiflexion, eversion and forefoot abduction for the ankle; and flexion, abduction and external rotation for the knee and hip), normalised to each participant's standing calibration trial, were then calculated at the time of IC and the time of the F_{AP} to determine lower limb alignment, as well as ROM, during the impact phase of landing.

The raw kinematic, GRF, free moment and centre of pressure data were filtered (see Chapters 4 and 5) prior to calculating the lower limb kinematics and joint moments. The ankle, knee and hip internal joint moments at the time of F_{AP} , were then calculated using an inverse dynamics approach.²² All joint moments were reported as absolute values (Nm), as well as normalised as a product of each participant's body mass and lower limb length (Nm/kg/m). Positive moments were defined as dorsiflexion, eversion and forefoot abduction for the ankle; extension, abduction and external rotation for the knee; and flexion, abduction and external rotation for the hip.

Following standard preparation,²³ the activity of medial gastrocnemius, tibialis anterior, vastus medialis, rectus femoris, semitendinosus and biceps femoris of each

participant's test limb was recorded using bipolar Ag-AgCl surface electrodes (2 cm inter-electrode spacing; Blue Sensor Type M-OO-S, Medico test, Denmark). Electromyographic signals from the electrodes were relayed to a Telemetry transmitter (Noraxon, USA; 1,000 Hz; bandwidth 16-500 Hz) and then to a Telemetry receiver via an antenna. All EMG data were then analysed using a custom-written LabVIEW software program (EMGAnalyser V3, 2011). Details on the EMG data processing and analyses are described in Chapters 4 and 5. Overall, the timing of muscle onsets relative to IC were determined throughout the four test sessions. Based on the timing of muscle onsets, muscle co-contraction was determined (using individual data). Co-contraction was determined for each participant as either "yes" (timing between two or more muscle-pair onsets < 50 ms apart) or "no" (timing of muscle-pair onsets > 50 ms between muscles). Note that co-contraction was only deemed in antagonist muscle pairs controlling the same joint (such as; medial gastrocnemius and tibialis anterior for the ankle and knee; as well as hamstring (semitendinosus and biceps femoris) and quadriceps (vastus medialis and rectus femoris) for the knee and hip). The kinematic, GRF and EMG data were time synchronised during data collection using First Principles software (Version 1.2.2; Northern Digital, Canada).

Statistical analyses

Means and standard errors were calculated for the three-dimensional ankle, knee and hip kinematics and joint moments, as well as the EMG timing data, for each of the four test sessions. A linear mixed model was used (repeated covariance type = compound symmetry; correlated residuals within the random effects) to determine any significant ($p \leq 0.05$) main effects of time on the dependent variables, controlling for growth variables (height, body mass, lower limb length) as covariates (which were

time dependent). The linear mixed model is a direct likelihood approach, which has been shown to be a suitable method for analysing longitudinal data with missing values, whereby the method assumes that data are missing at random.²⁴ Post-hoc comparisons were performed using a *t*-test with a Bonferroni adjustment. Muscle co-contraction data were calculated using a frequency analysis to describe the neuromuscular activation patterns during the horizontal landing movement. All statistical procedures were performed using SPSS (Version 20; SPSS Inc., Chicago, IL).

RESULTS

Lower limb kinematics

Participants displayed no significant change in ankle, knee or hip ROM from IC until F_{AP} in the sagittal ($p = 0.379$, 0.296 , and 0.964 , respectively), coronal ($p = 0.365$, 0.333 and 0.965 , respectively) or transverse planes ($p = 0.475$, 0.163 and 0.608 , respectively) over the four test sessions (see Figure 6.1). Furthermore, no significant changes in three-dimensional ankle alignment were displayed over the 12 months (see Figure 6.1a). However, there was a significant effect of time on knee flexion at F_{AP} ($p = 0.028$), whereby post-hoc analyses revealed significantly less knee flexion during Test 4 ($22.7 \pm 1.9^\circ$, $p = 0.017$) compared to Test 1 ($28.7 \pm 1.5^\circ$; see Figure 6.1b). Although, knee external rotation alignment did not change significantly with respect to time at IC ($p = 0.067$) or F_{AP} ($p = 0.065$), there were significant changes in hip flexion over time at IC ($p = 0.010$) and F_{AP} ($p = 0.047$), such that participants displayed significantly greater hip flexion during Test 4 ($39.2 \pm 2.0^\circ$ at IC and $41.3 \pm 2.0^\circ$ at F_{AP}) compared to Test 1 ($33.0 \pm 1.7^\circ$, $p = 0.014$ at IC; $35.8 \pm 1.7^\circ$, $p = 0.050$ at F_{AP}; see Figure 6.1c). Participants did not display a significant change in hip alignment in the

transverse plane throughout the 12 months at IC ($p = 0.198$) or F_{AP} ($p = 0.071$; see Figure 6.1c).

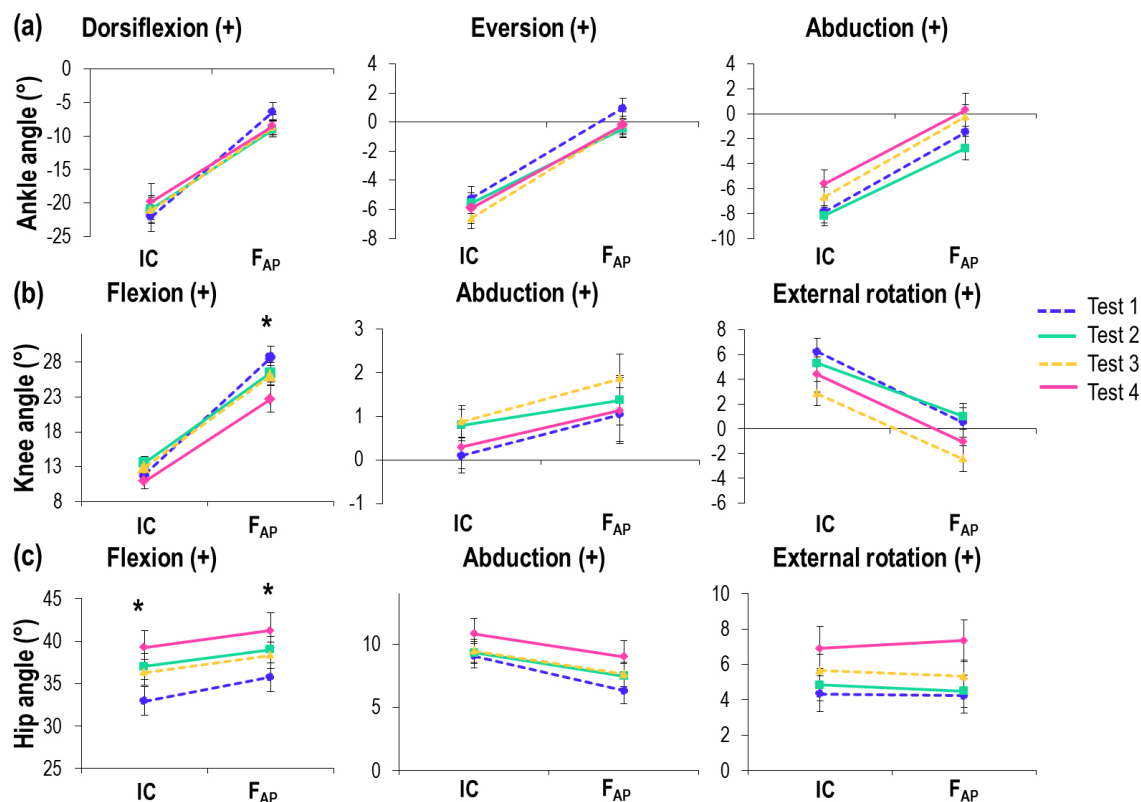


Figure 6.1: Means \pm SE for the three-dimensional (a) ankle (b) knee and (c) hip joint angles ($^{\circ}$) at the time of initial contact (IC) and peak anteroposterior ground reaction force (F_{AP}) during Test 1 ($n = 33$), Test 2 ($n = 46$), Test 3 ($n = 43$) and Test 4 ($n = 19$; * indicates a significant effect of time at $p \leq 0.05$).

Joint moments

No significant effect of time was found on the three-dimensional absolute or normalised internal ankle joint moments at F_{AP} (see Table 6.1). Participants, however, displayed significantly greater absolute ($p = 0.006$) and normalised ($p = 0.006$) knee abduction moments at F_{AP} during Test 2 compared to Test 4 (see Table 6.2). Despite no significant effect of time on the sagittal and transverse plane hip joint moments, significantly greater hip abduction moments were displayed during Test 1 compared to Test 3 ($p = 0.016$ for the normalised moments) and Test 4 ($p = 0.035$ and 0.006 for the absolute and normalised moments, respectively; see Table 6.3).

Table 6.1: Means \pm SE for the absolute and normalised internal ankle joint moments at the time of the peak anteroposterior ground reaction force throughout the four test sessions.

Variable	Test 1 (n = 33)	Test 2 (n = 46)	Test 3 (n = 43)	Test 4 (n = 19)	p-value
Absolute (Nm)^a					
Dorsiflexion	-30.34 \pm 3.93	-24.34 \pm 3.47	-29.72 \pm 3.47	-30.25 \pm 5.07	0.440
Eversion	-6.99 \pm 1.74	-6.03 \pm 1.58	-8.71 \pm 1.58	-7.16 \pm 2.14	0.390
Forefoot abduction	0.16 \pm 0.36	0.21 \pm 0.32	0.09 \pm 0.32	-0.28 \pm 0.44	0.741
Mass x leg length-normalised (Nm/kg/m)					
Dorsiflexion	-1.00 \pm 0.13	-0.75 \pm 0.11	-0.92 \pm 0.11	-0.82 \pm 0.17	0.392
Eversion	-0.26 \pm 0.06	-0.20 \pm 0.05	-0.26 \pm 0.05	-0.22 \pm 0.07	0.541
Forefoot abduction	0.001 \pm 0.01	0.005 \pm 0.01	0.005 \pm 0.01	-0.008 \pm 0.01	0.789

a. Positive internal joint moments: dorsiflexion, eversion, forefoot abduction.

Table 6.2: Means \pm SE for the absolute and normalised internal knee joint moments at the time of the peak anteroposterior ground reaction force throughout the four test sessions (* indicates a significant effect of time at $p \leq 0.05$).

Variable	Test 1 (n = 33)	Test 2 (n = 46)	Test 3 (n = 43)	Test 4 (n = 19)	p-value
Absolute (Nm)^a					
Extension	38.24 \pm 5.27	32.94 \pm 4.68	28.24 \pm 4.67	29.93 \pm 6.72	0.368
Abduction	2.17 \pm 1.78	4.08 \pm 1.56	0.32 \pm 1.56	-4.46 \pm 2.31	0.009*
External rotation	-3.20 \pm 0.83	-2.65 \pm 0.73	-1.28 \pm 0.73	-0.60 \pm 1.05	0.055
Mass x leg length-normalised (Nm/kg/m)					
Extension	1.32 \pm 0.17	1.03 \pm 0.15	0.86 \pm 0.15	0.73 \pm 0.22	0.057
Abduction	0.08 \pm 0.06	0.13 \pm 0.05	0.01 \pm 0.05	-0.15 \pm 0.08	0.008*
External rotation	-0.10 \pm 0.04	-0.08 \pm 0.03	-0.05 \pm 0.04	-0.03 \pm 0.04	0.060

a. Positive internal joint moments: extension, abduction, external rotation.

Table 6.3: Means \pm SE for the absolute and normalised internal hip joint moments at the time of the peak anteroposterior ground reaction force throughout the four test sessions (* indicates a significant effect of time at $p \leq 0.05$).

Variable	Test 1 (n = 33)	Test 2 (n = 46)	Test 3 (n = 43)	Test 4 (n = 19)	p-value
Absolute (Nm)^a					
Flexion	-33.38 \pm 3.84	-36.58 \pm 3.44	-40.99 \pm 3.44	-45.26 \pm 4.81	0.085
Abduction	15.06 \pm 3.11	11.73 \pm 2.82	8.12 \pm 2.82	3.87 \pm 3.82	0.024*
External rotation	12.68 \pm 1.87	14.17 \pm 1.63	12.76 \pm 1.63	12.82 \pm 2.47	0.890
Mass x leg length-normalised (Nm/kg/m)					
Flexion	-1.08 \pm 0.12	-1.15 \pm 0.11	-1.28 \pm 0.11	-1.25 \pm 0.15	0.426
Abduction	0.52 \pm 0.09	0.36 \pm 0.08	0.21 \pm 0.08	0.08 \pm 0.12	0.003*
External rotation	0.42 \pm 0.06	0.43 \pm 0.05	0.38 \pm 0.05	0.33 \pm 0.07	0.626

a. Positive internal joint moments: flexion, abduction, external rotation.

Muscle activation

There was no significant effect of time on the onset of medial gastrocnemius ($p = 0.571$), tibialis anterior ($p = 0.819$), rectus femoris ($p = 0.933$), semitendinosus ($p = 0.843$) or biceps femoris ($p = 0.403$) relative to IC. However, participants displayed significantly earlier activation of vastus medialis during Test 2 compared to Test 3 ($p = 0.030$; see Figure 6.2). Participants also displayed a reduction in hamstring-to-quadriceps muscle co-contraction throughout their growth spurt, whereby 54% of participants co-contracted their hamstring and quadriceps muscles prior to landing during Test 1, 60% during Test 2, 12% during Test 3 and only 8% during Test 4. A reduction in medial gastrocnemius-to-tibialis anterior muscle co-contraction was also displayed throughout the 12 months, such that 57% of participants co-contracted their medial gastrocnemius and tibialis anterior muscles prior to landing during Test 1, 59% during Test 2, 15% during Test 3 and 10% during Test 4.

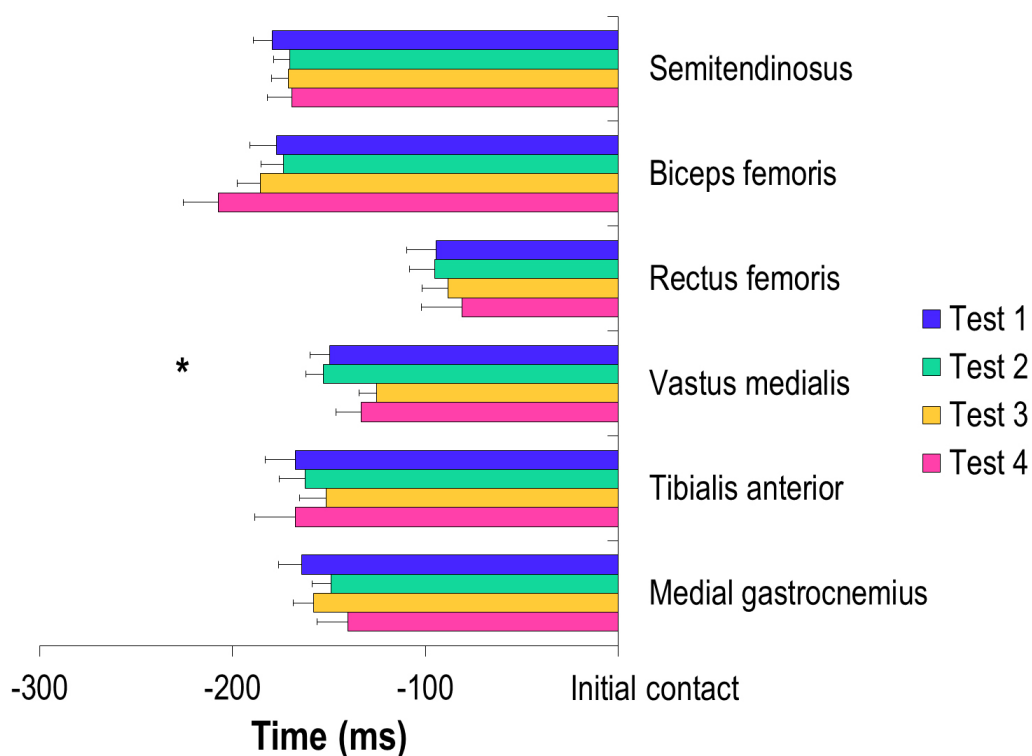


Figure 6.2: Means \pm SE for the timing of muscle onsets (ms) relative to initial contact during Test 1 ($n = 33$), Test 2 ($n = 46$), Test 3 ($n = 43$) and Test 4 ($n = 19$; a negative value indicates the muscle onset occurred prior to initial contact; * indicates a significant effect of time at $p \leq 0.05$).

DISCUSSION

The rapid lower limb musculoskeletal growth changes experienced by pubescent girls during their growth spurt (see Chapter 3) are thought to play a role in their increased ACL injury risk during dynamic landing movements (see Chapter 4). For this reason we investigated the longitudinal changes in the three-dimensional lower limb kinematics, joint moments and neuromuscular activation patterns displayed by girls during the performance of a horizontal landing task throughout their adolescent growth spurt. As hypothesised, girls displayed a change in their lower limb landing technique throughout their adolescent growth spurt, the results of which are detailed below.

Landing kinematics

During the earlier stages of pubescent growth (corresponding with Test 1-2 in the present study) girls displayed rapid growth of their lower limbs, weaker hamstring muscles relative to their quadriceps, as well as a decrease in passive knee joint stability (see Chapter 3). Despite substantial changes to their musculoskeletal structure and function throughout the 12 months of their growth spurt, girls in the present study displayed no significant changes in their three-dimensional ankle motion or joint loading during landing throughout this time. This finding is consistent with the results of Whitting et al.,²⁵ who concluded that ankle motion during a landing is dictated by the task itself, rather than being influenced by the structural or functional features of the individual. This would suggest that the musculoskeletal changes experienced by girls during the adolescent growth spurt (Test 1-4 in the present study; see Chapter 3), no matter how vast or rapid, are unlikely to alter ankle motion during the performance of a dynamic horizontal landing task.²⁵

During the transition from the earlier stages (Test 1) to the later stages of puberty (Test 4), girls in the present study displayed a reduction (approximately 10°) in knee flexion, which was accompanied by an increase in hip flexion (approximately 6°), during the performance of the horizontal landing task. Although we acknowledge between-study differences in landing task, chronological age and developmental stage, these results are consistent with findings by Hass et al.,²⁶ who reported pre-pubescent females (aged 8-11 years; pre-menarche) to display significantly ($p < 0.05$) greater knee flexion at IC during a box-drop landing compared to their post-pubescent (aged 18-25 years; 6 years post-menarche) counterparts (20° and 15°, respectively). Furthermore, Yu et al.,²⁷ reported adolescent females to display a reduction in knee flexion alignment upon landing, from 11 to 16 years of age. Similarly Swartz et al.²⁸ reported greater hip flexion at the time of peak GRF in post-pubescent females (38°; aged 19-29 years) compared to their pre-pubescent counterparts (31.5°; pre-menarche, aged 7-10 years), during a maximal vertical jump. Interestingly, girls demonstrate a reduction in lower limb flexibility (using the sit-and-reach test) around the time of PHV²⁹ (corresponding to Test 2), particularly of the hamstring muscles (using goniometric measurements of knee extension; see Chapter 3), which increases 8 months after PHV (around the time of Test 4 in the present study; see Figure 3.4). Although jump distance did not change over time, we speculate that the combination of more flexible (see Figure 3.4) and weaker (see Figure 3.6) hamstring muscles (relative to the quadriceps) during later puberty, may enable girls to ‘stretch-out’ more during landing, thus contributing to the longitudinal increase in hip flexion and decrease in knee flexion alignment. Therefore, given these longitudinal changes in sagittal plane knee and hip kinematics displayed by girls throughout the 12 months of their growth spurt, it is

important to examine whether this change in landing techniques places girls at an increased risk of injury.

Increased knee flexion has been suggested as a landing strategy to protect the internal structures of the knee²⁶ and decrease ACL injury risk.^{5, 6, 30} Knee flexion angles less than 22° during landing (as displayed by girls during Test 4; see Figure 6.1b), are thought to increase the potential of the quadriceps to strain the ACL, increasing the likelihood of ACL rupture.^{6, 30} In fact, Li et al.³¹ demonstrated that with an isolated quadriceps load (200 N), in-situ ACL loads were the highest (45 N) at 15° of knee flexion and decreased by approximately 10-15 N with every 15° increase in knee flexion. This suggests that the progressive decline in knee flexion displayed girls throughout puberty in the present study, may increase ACL loading and the potential for injury. Furthermore, Li et al.³¹ reported ACL loads to significantly reduce (by approximately 10 N) with the addition of an 80 N hamstring force. This highlights the protective role of the hamstring muscles during landing and again suggests a greater risk of ACL injury during the later stages of puberty, given the lag in hamstring strength development during this time (see Figure 3.6). Although all landings performed in this longitudinal study were non-injurious, the evidence would suggest that despite a decline in all growth velocities during Test 4 (see Figure 3.2), the transition in sagittal plane knee and hip joint alignment throughout the growth spurt may, in fact, lead to a posture associated with an increased ACL injury risk.^{5, 6, 30, 31}

Joint moments during landing

The rapid increase in the height of the centre of mass during puberty, has been suggested to reduce the ability to control body position during landing, potentially decreasing stability and increasing loads experienced at the knee.² Despite no change in

knee abduction alignment and contrary to a previous report,²⁶ girls in the present study displayed significantly greater internal knee abduction moments during Test 2 and internal knee adduction moments during Test 4 (see Table 6.2). Consistent with the present findings, Ford et al.³ reported that girls displayed an increase in peak internal knee adduction moments from the first to the second year of their growth spurt (-14.4 Nm and -19.2 Nm, respectively). Greater internal knee adduction moments have also been reported in females aged between 10-16 years, compared to their male counterparts (approximately 0.75 and 0.01 Nm/kg/m, respectively).³² This was thought to make girls more susceptible to ACL injury,^{3, 32} as increased internal knee adductor loads during landing have been shown to predict ($r^2 = 0.88$) ACL injury risk within 78% sensitivity.⁴ Furthermore, given the relative moment arms of the thigh musculature,³³ this also indicates that the girls tended to use their knee abductor muscles (vastus lateralis and lateral hamstrings) during early to mid-puberty (Test 2) to control knee abduction motion, whereas girls used their knee adductor muscles (vastus medialis and medial hamstrings) to control knee abduction motion during late puberty (Test 4). Furthermore, girls in the present study displayed a decrease in their hip abductor moments throughout the growth spurt (see Table 6.3), suggesting a net decrease in the use of their hip abductor muscles required to control hip adduction and ultimately, knee abduction.³⁴ Jacobs et al.³⁴ reported an association between lower peak isometric hip abductor torque (5.8% and 7.2% of BW x height for women and men, respectively) and increased knee abduction motion (7.3° and 3.3° for women and men, respectively) during a horizontal leap landing movement in adult females compared to males. Given that knee abduction alignment did not change throughout the 12 months, we speculate that the rapid increases in height and centre of mass displayed by girls during puberty,² in combination with their musculoskeletal changes^{2, 19} (see Chapter 3), may contribute

to a different strategy by which girls control coronal plane knee motion during landing, contributing to these altered knee and hip moments.

Muscle activation during landing

It is thought that the lag in the development of hamstring relative to quadriceps muscle strength throughout the adolescent growth spurt (see Figure 3.6), may influence the way the girls recruit their lower limb muscles during landing. Despite high between-subject and within-subject variation in the EMG data in the present study, the girls displayed significantly later activation of vastus medialis during the later stages of the growth spurt (from Test 3) compared to Test 2 (see Figure 6.2). Whilst a significant effect of time on biceps femoris activation was not evident in the present study (potentially due to high variation), Figure 6.2 shows that the girls activated biceps femoris much earlier during Test 4 compared to the previous testing sessions. Research has demonstrated that this pattern of muscle recruitment involving earlier hamstring followed by later quadriceps activation, typically displayed by adults, allows for the hamstring muscles to more effectively impart posterior drawer to the tibia in an attempt to protect the ACL.^{8,9} Therefore, we suggest that this muscle activation pattern may be an attempt to control the lower limb and thus protect the ACL due to the increased hip flexion and decreased knee flexion throughout the adolescent growth spurt.^{8, 9} Furthermore, girls in the present study displayed a reduction in the amount of muscle co-contraction (hamstring-to-quadriceps and medial gastrocnemius-to-tibialis anterior) utilised throughout their growth spurt. Co-contraction is suggested to be a motor control strategy that increases joint stability, indicative of an immature or low-skilled recruitment pattern,^{11, 35} commonly displayed by pre-pubescent children compared to their adult counterparts.¹⁰ Whilst it is acknowledged that determination of muscle

co-contraction in the present study was less complex compared to previous studies,¹⁰ this suggests that the increased co-contraction during Test 1-2 (early to mid-puberty, Tanner Stage II-III) may be an attempt to increase lower limb control and joint stability,¹⁰ during a period of rapid lower limb growth and musculoskeletal functional changes (see Chapter 3). However, given that girls experience an increased number of ACL injuries from the onset of puberty,¹ it is unknown whether this increased muscle co-contraction is, in fact, protective of the lower limb. Furthermore, whether the transition to a more asynchronous muscle pattern (hamstrings followed by the quadriceps) places girls at a decreased ACL injury risk still warrants further investigation.

To our knowledge, this is the first study to progressively track the changes in the three-dimensional ankle, knee and hip kinematics, joint moments and neuromuscular recruitment, displayed during the performance of a horizontal landing movement, in pubescent girls. However, several limitations of the present study are acknowledged. Firstly, to minimise participant burden only changes to lower limb biomechanics were monitored throughout the adolescent growth spurt. Research is recommended to examine changes to trunk biomechanics during puberty, which will provide further insight into the technique changes displayed by girls throughout the 12 months of their growth spurt. Again, in an attempt to minimise participant burden, only six lower limb muscles were investigated in the present study. We therefore recommend further research to explore changes to the hip abductor and lateral thigh muscles during puberty to provide further information to the changes in knee and hip abduction moments throughout the adolescent growth spurt in girls. We acknowledge that the best indicator of biological age is through x-rays to calculate skeletal age. However, due to ethical constraints placed on the present study, use of skeletal age was not possible, and

instead, Tanner staging and maturity offset were used to characterise pubertal and biological age. In addition, whilst the statistical method used in the present study was able to account for missing data, it is acknowledged that the discrepancy in the number of participants during each testing session is a study limitation. Finally, we acknowledge that the lack of physical activity data for each participant presents as a limitation, thereby suggesting the need for future studies to include these variables as covariates.

Overall, it was found that throughout the growth spurt girls displayed a longitudinal decrease in knee flexion alignment, increase in hip flexion alignment, increase in knee and hip adductor moments, as well as a reduction in muscle co-contraction in preparation to land. This demonstrates a change in strategy with which pubescent girls control their lower limb, potentially due to the longitudinal musculoskeletal changes occurring during this period of growth. The outcomes of this research provide a greater understanding of the changes in landing strategy used by pubescent girls throughout the adolescent growth spurt.

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Chapter 7

Summary, conclusions and recommendations for future research.

SUMMARY

The rapid musculoskeletal and oestrogen changes from the onset and throughout puberty in girls¹⁻⁹ are thought to play a role in their increased risk of non-contact ACL ruptures compared to their male counterparts. There are conflicting reports, however, on the effect of oestrogen on the ACL, as well as the lower limb musculoskeletal and knee joint laxity changes that occur during puberty. Furthermore, the influence of these musculoskeletal and oestrogen changes on the lower limb landing biomechanics displayed by pubescent girls are relatively unknown. Therefore, the primary purpose of this thesis was to investigate the longitudinal changes in musculoskeletal structure and function, as well as the oestrogen levels, during the adolescent growth spurt in girls and the influence of these changes on lower limb landing biomechanics.

Forty-six healthy girls, aged between 10-13 years, were recruited for this longitudinal study based on their pubertal development (Tanner Stage II-III) and maturity offset (-6 to -4 months or 0 months). Participants were then tested up to four times during the 12 months of their adolescent growth spurt, according to the estimated timing of their maturity offset (Test 1: maturity offset = -6 to -4 months, Test 2: maturity offset = 0 months, Test 3: maturity offset = +4 months, Test 4: maturity offset = +8 months). Each participant's anthropometric characteristics, oestrogen levels, anterior knee joint laxity, lower limb flexibility and isokinetic strength, and landing biomechanics were collected and recorded during each of the laboratory-based test sessions. The landing task performed was a horizontal leap movement during which GRF, lower limb EMG and three-dimensional kinematic data (100 Hz) were collected.

Monthly tracking was also conducted in each participant's home, so as to estimate maturity offset using the anthropometric data, as well as to determine monthly fluctuations in lower limb flexibility and strength. The results from this longitudinal study were analysed and presented in four chapters (see Chapters 3-6), with each chapter systematically contributing to the overall thesis aim.

Due to disparities in the literature regarding the musculoskeletal and oestrogen changes during puberty in girls (see Chapter 2), the first experimental chapter of this thesis (see Chapter 3), investigated the longitudinal changes in oestrogen, as well as anterior knee laxity and lower limb strength and flexibility throughout the adolescent growth spurt in girls. It was hypothesised that girls would display a consistent increase in hamstring and quadriceps muscle strength without an apparent muscle strength 'spurt' and a decrease in lower limb flexibility around the time of PHV, as well as a rapid increase in oestrogen and anterior knee laxity throughout the growth spurt. Consistent with previous literature,^{8, 10} it was found that throughout the 12 months of their growth spurt, girls displayed peak leg length growth prior to PHV and peak torso growth after PHV. In partial agreement with the hypothesis, it was found that from the time of PHV (where girls were growing at a rate of 10 cm/yr), participants displayed significantly greater anterior knee laxity, a reduction in hamstring flexibility, accompanied by a significant increase in isokinetic quadriceps strength over time, although no concurrent increase in isokinetic hamstring muscle strength was displayed. However, contrary to the original hypothesis, no significant increase in oestrogen concentration was displayed throughout the 12 months of the adolescent growth spurt. It was speculated that the changes in anterior knee laxity and lower limb strength and flexibility could be attributed to factors outside of the influence of oestrogen alone. Furthermore, during the period of PHV and rapid lower limb growth (early stages of

puberty; Test 1 and 2), the combination of lower hamstring flexibility, increased anterior knee laxity and the lag in development of hamstring muscle strength relative to quadriceps muscle strength is likely to contribute to a decrease in knee joint stability during landing tasks, ultimately affecting lower limb landing biomechanics displayed by these pubescent girls, although this notion warrants further investigation.

The results of Chapter 3 identified the need to determine whether these longitudinal changes in hamstring strength and anterior knee joint laxity affected the landing technique displayed by these girls during their adolescent growth spurt. Therefore, the effects of altered hamstring strength (see Chapter 4) and anterior knee joint laxity (see Chapter 5) on the lower limb landing biomechanics of pubescent girls were investigated. Specifically, due to the lag in the development of hamstring muscle strength relative to quadriceps muscle strength displayed by girls throughout their growth spurt identified in Chapter 3, the aim of Chapter 4 was to determine whether pubescent girls with lower hamstring muscle strength displayed different lower limb biomechanics when landing from a leap compared to girls with higher hamstring muscle strength. It was hypothesised that girls with lower hamstring strength would display significantly lower hamstring-to-quadriceps ratios, as well as significantly different lower limb kinematics and kinetics, including higher estimated ACL loading and altered muscle activation patterns, during landing compared to girls with higher hamstring strength. Overall, the results of this chapter revealed that girls with lower hamstring strength displayed significantly lower hamstring-to-quadriceps ratios, particularly when tested at the sagittal plane of knee angle corresponding with the average knee alignment displayed by the girls at the time of the peak anteroposterior GRF during landing. This finding suggests that girls with lower concentric hamstring muscle strength might have a reduced capacity of their hamstring muscles to protect the ACL during landing.

Furthermore, during the landing movement, girls with lower hamstring muscle strength displayed greater knee abduction alignment, reduced hip abduction moments and greater estimated ACL loading at the time of the peak anteroposterior GRF compared to their counterparts with higher hamstring muscle strength. These results suggest that girls with reduced hamstring strength have a decreased capacity to control lower limb frontal plane alignment during landing, which may contribute to increased estimated ACL loading in girls with lower hamstring strength.

The results of Chapter 3 also revealed that the girls displayed a significant increase in anterior knee laxity throughout the 12 months of their adolescent growth spurt, particularly from the time of PHV. As increased anterior knee laxity is predictive of ACL injury¹¹ and is thought to contribute to a decrease in knee joint stability,¹² Chapter 5 investigated whether pubescent girls with higher anterior knee laxity at the time of their PHV displayed differences in lower limb strength as well as lower limb biomechanics when landing after performing a horizontal landing movement compared to girls with lower anterior knee laxity. It was hypothesised that, compared to girls with lower anterior knee laxity, girls with higher anterior knee laxity would display significantly greater isokinetic strength, altered lower limb kinematics, higher kinetics, as well as significantly earlier lower limb muscle onsets relative to IC. Interestingly, despite original speculations, girls with higher anterior knee laxity displayed similar hamstring and quadriceps isokinetic strength, as well as similar ankle and knee landing kinematics compared to their counterparts with lower anterior knee laxity. However, girls with higher anterior knee laxity displayed reduced hip abduction alignment, increased hip abduction moments, as well as significantly earlier hamstring and later TA activation prior to landing. It is speculated that this muscle recruitment strategy may be a compensatory mechanism used by girls with higher knee laxity; the earlier hamstring

muscle activation in particular, may reduce the ability of the muscles to act synergistically to protect the ACL, increasing the likelihood of injury.

Due to the rapid musculoskeletal structural and functional changes experienced throughout puberty (see Chapter 3), the final experimental chapter of this thesis (see Chapter 6) attempted to link these musculoskeletal changes with the longitudinal development in the three-dimensional lower limb landing kinematics, joint moments and muscle activation patterns displayed by the girls during the performance of a horizontal landing task throughout the adolescent growth spurt. It was hypothesised that girls would display significant changes in their three-dimensional lower limb ROM and alignment, specifically an increase in knee abduction; increased joint loading, such as an increase in coronal plane knee moments; as well as changes in their lower limb neuromuscular recruitment, including a decrease in muscle co-contraction, throughout the adolescent growth spurt. Results of the study revealed that throughout their growth spurt girls displayed a longitudinal decrease in knee flexion alignment, an increase in hip flexion alignment and an increase in knee and hip adductor moments upon landing, as well as a reduction in muscle co-contraction in preparation to land. These technique changes during the adolescent growth spurt highlighted a change in strategy used by the pubescent girls in an attempt to control their lower limbs during landing. It is speculated that these technique changes were required due to the rapid and differential musculoskeletal structural and functional changes that occurred during this 12-month period of growth.

CONCLUSIONS

Based on the findings of this thesis it was concluded that during the adolescent growth spurt, pubescent girls display rapid growth of their lower limbs, an increase in

anterior knee laxity, as well as a lag in development of their hamstring muscle strength relative to their quadriceps muscle strength. The combination of these rapid and differential musculoskeletal structural and functional changes are thought to decrease knee joint stability during landing and are likely to contribute to the changes in landing technique that were evident during this time of rapid growth. The outcomes of this research provide a greater understanding of the lower limb musculoskeletal structural and functional changes throughout the adolescent growth spurt in girls, as well as the influence of these changes on landing technique in these pubescent girls.

RECOMMENDATIONS FOR FUTURE RESEARCH

Based on the studies conducted for this thesis, the following recommendations for future research are made:

- When lower limb flexibility was measured every 4 months throughout the adolescent growth spurt, no significant change in ROM was detected. Participants, however, displayed a significant reduction in hamstring flexibility just prior to PHV when flexibility was measured every month. These results suggest that month-to-month measurements of flexibility may be more sensitive to the changes occurring during puberty than measurements taken every 4 months. Therefore, regular monitoring of girls throughout puberty should be conducted to detect changes in lower limb flexibility and potential ‘at risk’ times during the adolescent growth spurt.
- Although controversial, previous research has reported an association between peak levels of oestrogen throughout the menstrual cycle and increasing anterior knee laxity. However, despite the participants displaying a significant increase in anterior knee laxity throughout the adolescent growth spurt, there was no

concurrent increase in oestrogen concentration. It is suggested that hormonal measurements every 4 months may not be sensitive enough to detect subtle changes in oestrogen during the growth spurt in girls and further research, using other non-invasive techniques (such as urine), should measure oestrogen more regularly, such as on a daily basis.

- Seasonal changes in sporting activity may have contributed to an increase in variability of the results, suggesting the need for future studies to incorporate this variable as a potential confounding factor when assessing musculoskeletal structure and function, as well as landing biomechanics throughout the adolescent growth spurt.
- Girls displayed a rapid increase in torso length towards the end of the growth spurt (from Test 3). Motion of the trunk during landing has the potential to alter lower limb biomechanics and ACL injury risk. Therefore, further research is warranted to determine how the rapidly changing inertial properties of the torso during puberty alter landing biomechanics, and ultimately ACL injury risk.
- Throughout the adolescent growth spurt, girls displayed a lag in the development of their hamstring relative to their quadriceps muscle strength. This imbalance between hamstring and quadriceps muscle strength contributed to a decrease in knee frontal plane control, possibly increasing ACL load during landing. Therefore, further research is warranted to investigate the effect of increasing hamstring muscle strength or improving the hamstring-to-quadriceps strength balance on lower limb landing biomechanics in an attempt to reduce the incidence of ACL injury in the pubescent female population.
- Finally, although the present thesis provides speculation on how the results may affect ACL injury risk, it is imperative to determine whether the changes in

landing strategy displayed by girls throughout the adolescent growth spurt places them at an increased injury risk. This will allow better identification of 'at risk' landing biomechanics and therefore provide further evidence upon which to develop training programs that promote safer landing technique in pubescent girls.

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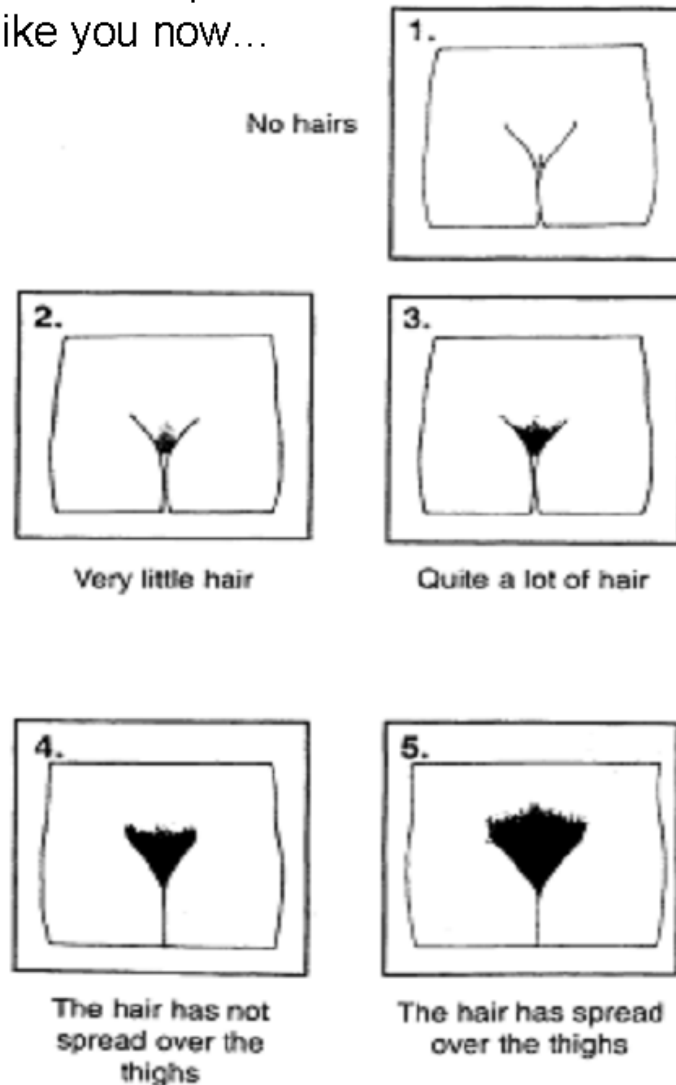
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APPENDICES

Appendix A

Simplified line drawings used to determine Tanner stage of pubertal development.¹

Circle the picture that most looks like you now...



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1. Taylor S, Whincup P, Hindmarsh P, Lampe F, Odoki K, Cook D. Performance of a new pubertal self-assessment questionnaire: A preliminary study. *Paediatric and Perinatal Epidemiology*. 2001; 15(1): 88-94.

Appendix B

Methods used to estimate maturity offset.

Sex-specific multiple regression equation:¹

Maturity offset = $[-9.376 + (0.0001882 * \text{Leg Length} * \text{Sitting Height}) + 0.0022 * (\text{Age} * \text{Leg Length}) + (0.005841 * \text{Age} * \text{Sitting Height}) - (0.002658 * \text{Age} * \text{Mass}) + (0.07693 * \text{Mass by Height Ratio})]$

Whereby:

- Age (decimal age in years): calculated by subtracting date of birth from the date of measurement
- Mass: measured with minimal clothing and shoes removed (kg)
- Leg length and sitting height: measured with shoes removed (cm)
- Mass by height ratio: calculated as (body mass/standing height) * 100

Determination of sitting height and leg length used in the regression equation:

- Standing height: Measured using the stretch stature method (with each participant's shoes removed). Standing height was measured as the maximum distance from the floor to the vertex of the head (the highest point on the skull when the head is held in the Frankfort plane).
- Sitting height: Measured using the stretch stature method (with each participant's shoes removed). The participants were seated on a measuring box (of known height; cm), with their hands resting on their thighs. Sitting height

was measured as the maximum distance from the vertex to the base of the sitting surface

- As the present study used a floor stadiometer, sitting height was calculated as the maximum distance from the vertex of the head to the floor minus the height of the measuring box.
- Leg length: Calculated by subtracting each participant's sitting height (cm) from their standing height (cm).

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“To infinity and beyond...”

– Buzz Lightyear, Toy Story